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ASSESSMENT OF THE FLAMMABILITY OF AIRCRAFT HYDRAULIC FLUIDS

Leo Parts

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This technical report has been reviewed and is approved for publication.

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The main thrust of the program was directed toward two objectives: (1) development of apparatus for the measurement of ignitability characteristics of fluids at high temperatures (up to 930°C), and (2) the use of that and other apparatus for the determination of ignitability, flame propagation properties, and heats of combustion of a number of aircraft fluids. These included currently used

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hydraulic fluids, candidate nonflammable hydraulic fluids, and other aircraft fluids such as lubricants, fuels, and heat transfer fluids.

The studies were successful in the identification of candidate non-flammable hydraulic fluids. These fluids were identified as Halocarbon® AO-8, Freon® E6.5, and Brayco® 814Z.

A semiautomatic ignition test apparatus was built that can be used for measurements at temperatures up to 1000°C. The operation range of a hot manifold ignition test apparatus was extended up to 930°C.

PREFACE

Numerous people materially contributed to the development of apparatus and techniques, and to the acquisition of information summarized in this report. They include the Project Engineer, Mr. G. Gandee, and Mr. W. Allen, Mr. B. Campbell, Mr. F. Sheldon, Dr. E. Snyder and Mr. F. Straus of the U.S. Air Force; Mrs. L. Gschwender from the University of Dayton Research Institute; Messrs. W. Calloway, W. D. Dillon, C. T. Dresner, P. F. Heimsch, H. J. Larrigan, L. R. Stark, W. N. Trump, and J. C. Wahl of Monsanto Company; Messrs. J. D. Arehart, F. N. Hodgson, A. M. Kemmer and J. D. Tobias of Monsanto Research Corporation.

The results summarized in this report are the product of a joint effort by all participants.

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SUMMARY

The main thrust of the program was directed toward two objectives: (1) development of apparatus for the measurement of ignitability characteristics of fluids at high temperatures (up to 927°C, 1700°F), and (2) use of that and other apparatus for the determination of ignitability and flame propagation properties and heats of combustion of a number of aircraft fluids. These included candidate nonflammable hydraulic fluids of different chemical types, currently used hydraulic fluids, lubricating oils, fuels, and heat transfer fluids.

A semi-automatic autoignition test apparatus was built that can be used for measurements at temperatures up to 1000°C (1830°F). The operating range of a hot manifold ignition test apparatus was extended up to 927°C (1700°F). A laboratory-scale surface ignition test apparatus was developed that can be used for measurements up to the latter temperature.

Three types of ignition measurements were conducted with the fluids to simulate different potential accident situations. These entailed determination of: (1) autoignition temperatures in a uniformly heated volume, (2) ignition temperatures upon impingement of liquid streams and sprays onto a hot manifold, and (3) ignitability of liquid sprays by an open flame (propane torch).

Among the chemically different types of candidate nonflammable hydraulic fluids, the organic compounds of high fluorine content (ethers and chlorofluorocarbons) exhibited the optimum combination of desirable fire performance characteristics. This includes a high ignition temperature, low propensity to propagate flames, and a low heat of combustion. The fluids that met the Air Force criteria for nonflammable hydraulic fluids are identified as: Halocarbon® AO-8, produced by Halocarbon Corporation, Freon® E6.5, a Du Pont Company Product; and Brayco® 8142 from Bray Oil Company. A 16 mm documentary film, depicting the performance of both the currently used and the candidate nonflammable hydraulic fluids, was produced as part of this effort.

INTRODUCTION

The main objective of the studies summarized in this report was to contribute to enhanced crew and aircraft survivability in normal and hostile operational environments. This objective was to be attained through an investigation of the ignitability and flame propagation characteristics of aircraft hydraulic fluids. The results of these investigations are to serve as a basis for Air Force review of the fire-protective design features of presently operational aircraft and for the design of future high-performance aircraft.

The Air Force interest in the assessment of the flammability characteristics of current and future hydraulic fluids was the driving force for this program. The Air Force, based on data relating to hydraulic fluids fires, has developed goals for both near-term and future applications. The criteria of interest for the program were those for the near term, or Criteria B. Criteria A represent the ultimate desired performance that may or may not be achieved.

FLAMMABILITY CRITERIA*

Test Method	Criteria "A" (rejected take off)	Criteria "B" (minimum acceptable)
<u>Heat of Combustion</u> (ASTM D-240 bomb method)	0 cal/g (0 Btu/lb)	<2.78 kcal/g (<5000 Btu/lb)
<u>Hot Manifold Ignition</u> (Modified federal test standard 791B-Method 6053)	>1649°C (>3000°F)	>927°C (>1700°F)
<u>Minimum Autogenous Ignition Temperature</u> (ASTM D-2155 modified to include injection pressure to 68 atm (1000 psig))	>1427°C (>2600°F)	>704°C (>1300°F)
<u>Atomized Fluid Flammability Test</u> (a) arc/spark (b) propane-air flame (c) incendiary ignitor	Fluid may ignite, but must be self-extinguishing	

*Established by ASD/ENFED, AFAPL/SFH

The term "nonflammable," as used in this report with reference to a fluid, implies that this fluid either meets or closely approaches the specifications of Air Force Flammability Criteria "B." However, it should be noted that under very intense fire or heat exposure conditions, in oxygen-containing atmosphere, the "nonflammable" fluid may ignite and burn.

The establishment of Criteria B was strongly influenced by the prior history of aircraft hydraulic fluid fires and some basic flammability considerations. The low heat of combustion, for example, would ensure minimal heat release from the burning fluid in any fire scenario. The elevated temperature requirements for hot surface and autoignition are related to the brake assembly of the aircraft. On a maximum braking effort under rejected take-off conditions, temperatures can reach 927°C (1700°F).

Prior testing of aircraft fluids indicated that the autoignition temperatures (AIT) were about 222°C (400°F) lower than the hot surface ignition temperatures. The limited quantities of fluids available, their high costs, and the previously noted hot surface ignition temperature led to the establishment of the 704°C (1300°F) AIT as the initial evaluation criterion for the candidate hydraulic fluids.

The ease of ignition of a fluid is greatly influenced by the degree of dispersion. The hydraulic fluid systems operate at the pressure of 204 atmospheres (3000 psi). A leak in the system could result in a spray. The most conducive conditions for ignition of the spray would involve highly atomized fluid. Hot surfaces and open flames would constitute ignition sources. The latter conditions, utilizing a propane torch for simulation, represent the most severe test conditions for the ignition of fluids.

The program provided for a logical progression in the assessment of the flammability of the fluids. First, the performance of the current fluids such as MIL-H-5606, MIL-H-83282 and Skydrol 500B (commercial airline fluid) was determined. The baseline performance of these fluids, in some instances, influenced the establishment of the final screening tests for the candidate nonflammable hydraulic fluids. The normal test sequence entailed initial screening of the candidate fluids, using the heat of combustion as the basic criterion. The fluids meeting this criterion were considered candidates for additional testing for the hot manifold tests.

Additional data were collected on various other types of fluids of interest to the Air Force. These data were primarily used for comparison purposes. Photographic documentation, including both still and motion pictures, was obtained for typical tests.

To characterize fire safety properties of candidate hydraulic fluids, apparatus was required whose operational temperature range would extend beyond that of conventional equipment. A semiautomatic autoignition test apparatus was built that can be used at temperatures up to 1000°C (1830°F). The hot manifold surface ignition test apparatus was operated at temperatures extending up to 927°C (1700°F). A small laboratory-scale surface ignition test apparatus was developed that can be operated at temperatures up to 927°C (1700°F).

The most pertinent data for analyzing safe use conditions of aircraft fluids are summarized in Tables 4 and 5 on pp. 42 and 46, respectively.

EXPERIMENTAL APPARATUS AND PROCEDURES

I. DETERMINATION OF AUTOIGNITION TEMPERATURES

The determination of autoignition temperatures (AIT's) of fluids with the apparatus designed in the 1950's (1) and specified in the ASTM Standard Method D2155-66 (2) was found to require an excessive amount of time. The attainment of uniform temperature in the sample compartment by use of three manually controlled heaters is the major reason for the excessive time requirement for this test.

A semi-automatic autoignition test apparatus had been developed at the Monsanto Industrial Chemicals Company (3). This apparatus employs only one heater and an air-circulating fan; its temperature is controlled automatically. The sample flask and its position in the furnace are identical with those of ASTM Standard Method D2155-66. Such a system, incorporating updated electronic components, was built under the present contract. This system is described briefly in the following section.

A. Description of the Autoignition Test Apparatus

The entire system is depicted in Figure 1. The major components of this system are the furnace (Lindberg, heavy duty crucible furnace, Model 56622), temperature controller (Lindberg, heavy duty, Model 59344), and the digital thermometer (Newport Laboratories, Inc. Model 2600).

The furnace can be heated to 1000°C (1830°F). It is powered by a 230 VAC line. Its maximum power consumption is rated at 2448 watts.

The controller can be used to maintain the temperature in the range from 200°C to 1200°C (392°F to 2192°F). The following specifications have been provided by the manufacturer:

---

(1) M. G. Zabetakis, A. L. Furno, and G. W. Jones, "Minimum Spontaneous Ignition Temperatures of Combustibles in Air," *Ind. Eng. Chem.* 46, 2173 (1954).

(2) "Standard Test Method for Autoignition Temperature of Liquid Petroleum Products," ASTM Designation D2155-66, Annual Book of ASTM Standards, Part 24, 1976.

(3) Private communication from W. N. Trump, Monsanto Industrial Chemicals Company.

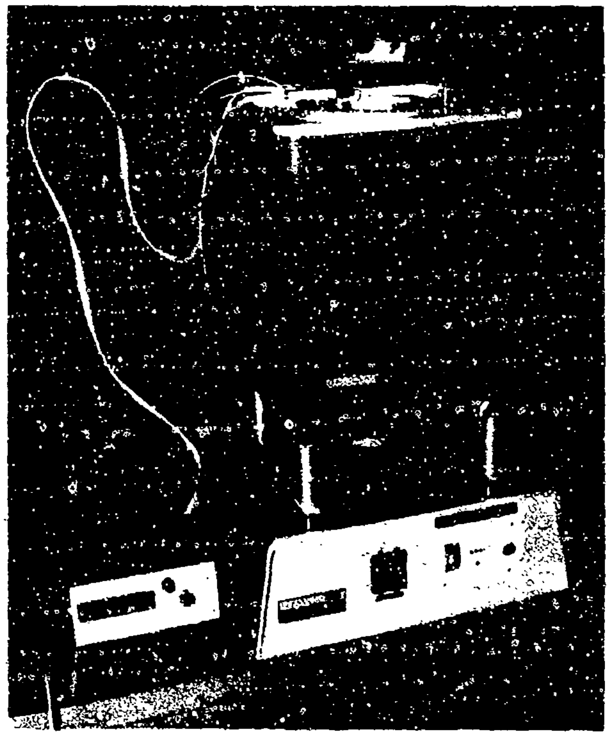

Figure 1. Autoignition test apparatus.

Control setability 0.5°C or better
Sensitivity typically 0.1°C
Accuracy typically 0.5°C
Long term stability typically 0.5°C over a 1-week period
Maximum current rating 30A
Maximum loading 6 kW.

A Platinel II (Type F) sensing thermocouple, enclosed in a stainless steel sheath, is used with the controller.

The multipoint digital thermometer is used to monitor the temperature in the three positions specified in the ASTM test procedure. The thermometer has a resolution of 0.1°C. The specifications include:

Repeatability ±1 count for 30 min at constant temperature
Sensitivity typically 0.3 μV per count
Zero stability ±0.5 μV/week.

For compactness, the furnace is mounted on top of the controller. The motor for air circulation is mounted on the base of the furnace (see Figure 2). The close-tolerance drive shaft does not allow air to enter the heated chamber from the bottom.

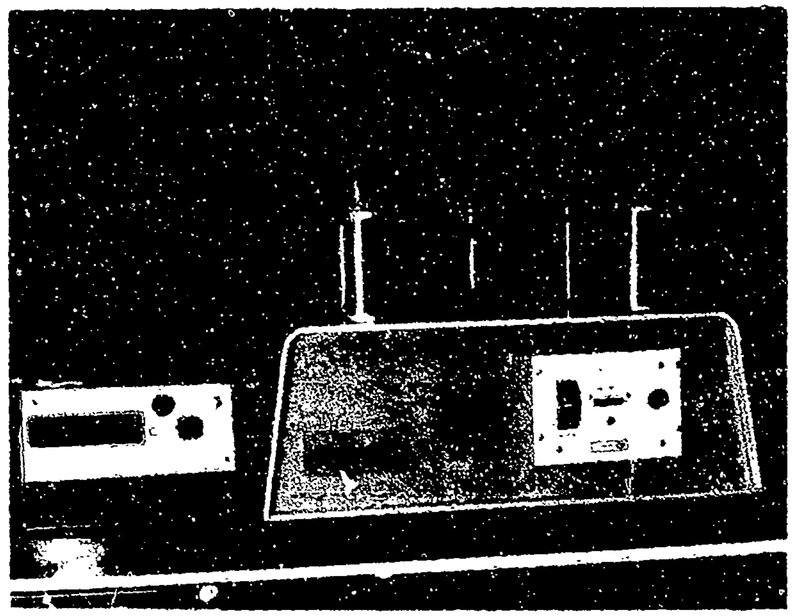

Figure 2. Closeup view of the chamber air circulation assembly and temperature controller.

The 250-ml Vycor sample flask is contained in an assembly supported by the insulating, removable cover plate (see Figures 3 and 4). This assembly also contains the thermocouples 2-4 for monitoring the flask temperature at three different elevations, thermocouple 1 for measuring the chamber air temperature, and thermocouple C for controlling the temperature.

A vertical, cylindrical baffle and two horizontal baffle plates have been incorporated into the apparatus to attain temperature uniformity in the heated sample chamber.

The sample is introduced with a syringe; it is observed with the assistance of a mirror placed above the Vycor flask.

B. Performance Characterization of the Autoignition Test Apparatus

Adjustments were made on the temperature controller to attain an optimum balance of performance with regard to the heating rate, and to the temperature stability after the desired temperature had been attained.

With the selected settings, the furnace could be heated from room temperature to 1000°C (1832°F) in 85 minutes. Thermal reequilibration within 50°C (90°F) of a set value required less than 30 minutes.

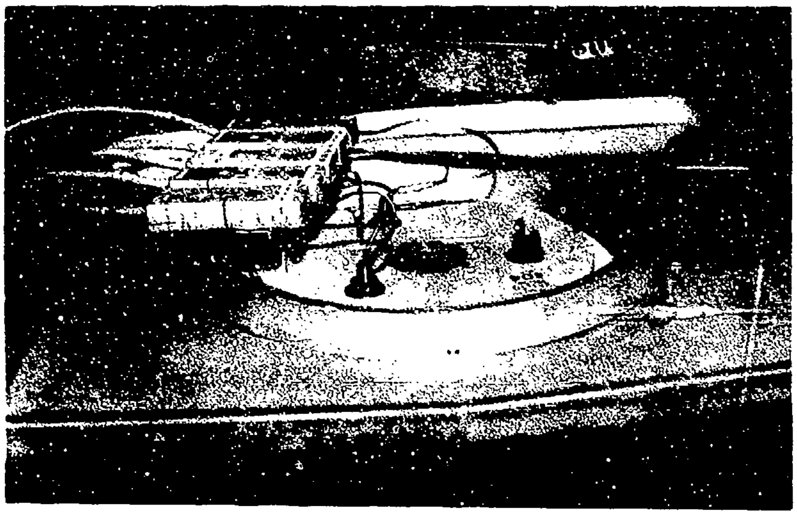

Figure 3. Top view of the autoignition test apparatus.

Figure 4. Top assembly of the apparatus, consisting of the support plate, sample flask, a horizontal baffle, and thermocouples.

Temperature stability was tested in three temperature ranges in which the apparatus was expected to be used. The following results were obtained by making ten measurements in 1-minute intervals:

Average temperature (°C)[a]	Temperature range (°C)[a]	Standard deviation (°C)[a]
241.4	241.2 - 241.6	0.18
590.1	590.0 - 590.2	0.09
950.4	950.4 - 950.5	0.05

[a]As determined with thermocouple 3 (see Figure 4), positioned on the outside surface of the sample flask, at the same elevation as the thermocouple C that is used as the sensor for controlling the furnace temperature.

The above data indicate that the desired testing temperature can be attained rapidly and maintained within very close limits with this autoignition test apparatus.

The vertical temperature profile within the 13.3 cm (5-1/4 inches) high sample flask was also determined. A temperature gradient was found to exist under the selected high-temperature furnace operating conditions, as indicated by the following data:

Temperature of the outside surface of the flask below the bottom (Thermocouple 2 in Figure 4)	958.3°C
Temperature inside the flask at the center of the bottom	957.1°C
Temperatures inside the flask, along the vertical axis, at the following distances above the bottom surface:	
2.5 cm (1 inch)	956.1°C
5.1 cm (2 inches)	952.1°C
7.6 cm (3 inches)	945.4°C
8.9 cm (3.5 inches)	936.4°C

The temperature gradients in the sample flask were highest near the opening. They were caused mainly by the cold air entering through the top opening and causing a convective flow.

As a test of performance, the autoignition temperature (AIT) of a reference fluid, Skydrol® 500B (Lot QH20121), was measured. The AIT determined with the newly built system, 510°C (950°F), was found to duplicate previous data obtained with another system at the Monsanto Industrial Chemicals Company (4).

(4) Memorandum from P. F. Heimsch, October 7, 1976.

C. Autoignition Testing Procedure

A procedure was developed for conducting autoignition tests with a minimal expenditure of time. In this procedure, the measurements are started above the estimated autoignition temperature of the fluid. A 0.10-ml sample is introduced into the flask with a hypodermic syringe. The contents of the flask are observed until ignition occurs, or for five minutes if ignition does not occur.

Thermocouple 2, positioned just below the bottom of the flask and in contact with it, is used for determining the autoignition temperature.

When ignition has been observed with a sample, the test temperature is lowered by 160°C or 80°C. The extent to which the temperature is lowered is based upon the vigor with which the ignition occurs. The stepwise lowering of temperature is repeated until ignition does not occur. When such a temperature is reached, the test temperature is increased by one half of the last increment. This procedure of raising or lowering the test temperature by one half of the preceding incremental value is repeated until the autoignition temperature is established within a 5°C (9°F) range with the 0.10-ml sample. Thus, the following temperature increments may be used: 160°C, 80°C, 40°C, 20°C, 10°C and 5°C. Significant saving of time is achieved by the systematic incremental change of test temperature.

After the autoignition temperature has been established with the 0.10 ml sample, tests are conducted also with 0.05 ml and 0.20 ml samples. The initial tests with the latter two quantities are conducted 5°C below the AIT established with the 0.10 ml sample. The lowering of the temperature in 5°C steps, in tests with 0.05 ml and 0.20 ml samples, is continued until ignition does not occur. The lowest temperature at which ignition occurs with either 0.05 ml, 0.10 ml, or 0.20 ml test sample is recorded as the AIT for the fluid.

Usually, the AIT has not been found greatly affected by the sample volume, within the 0.05 to 0.20 ml range. With fire-resistant fluids, it has been necessary to use 0.20-ml samples to establish the lowest temperature at which autoignition can be detected.

II. MEASUREMENT OF THE HEATS OF COMBUSTION

Heats of combustion measurements were conducted with an oxygen bomb calorimeter (Parr Instrument Company, Model A13) by the isothermal method (5). The measurement accuracy was checked by

(5) "Standard Test Method for the Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter," ASTM Designation D240-76, Annual Book of ASTM Standards, Part 23, 1976.

determining the heat of combustion of benzoic acid. The experimentally measured value was 2.648×10^7 J/kg (11,376 Btu/lb); the reported value is 2.644×10^7 J/kg (11,359 Btu/lb) (6).

Because of the fire-resistant characteristics of some fluids, benzoic acid had to be incorporated with the samples to attain more complete combustion. Even in the presence of benzoic acid, the combustion of some materials was incomplete. The data were always corrected for the quantities of benzoic acid added, presuming that it burned completely. Results obtained with samples containing benzoic acid are identified by a footnote in Table A-2.

III. DETERMINATION OF HOT MANIFOLD IGNITION TEMPERATURES

The hot manifold ignition test is used to determine the relative ignitability of liquids upon impingement onto a hot, cylindrical surface (7). To simulate different accident situations, the fluids were delivered either as fluid streams (from a burette or a beaker), or as sprays. The hot manifold ignition test apparatus used in this program (see Figures 5 and 6) is located at the Monsanto Fire Safety Test Laboratory in St. Charles, Missouri. This apparatus differs from that described in the Federal Test Method Standard 791B in the following respects:

(a) The manifold surface can be heated to 927°C (1700°F) [vs 704°C (1300°F) specified].

(b) The enclosure is larger, to reduce reflective heating.

A. Description and Performance Characterization of the Hot Manifold Ignition Test Apparatus

1. The Enclosure

The enclosure built for supporting and housing the manifold is 51 cm (20 in.) wide, 76 cm (30 in.) deep and 76 cm (30 in.) high. It provides a distance of 34 cm (13.5 in.) between the heated manifold and the rear wall of the enclosure. Reflected energy feedback to the manifold and heating of vapors by reflected radiation are reduced significantly by the increased distance (34 cm vs 11.4 cm; 13.5 vs 4.5 in.) between the manifold and the rear wall of the enclosure.

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(6) "Oxygen Bomb Calorimetry and Oxygen Bomb Combustion Methods," Parr Manual No. 120, Parr Instrument Company, Moline, Ill., 1948.

(7) "Manifold Ignition Test," Federal Test Method Standard No. 791B, Method 6053, 15 January 1969.

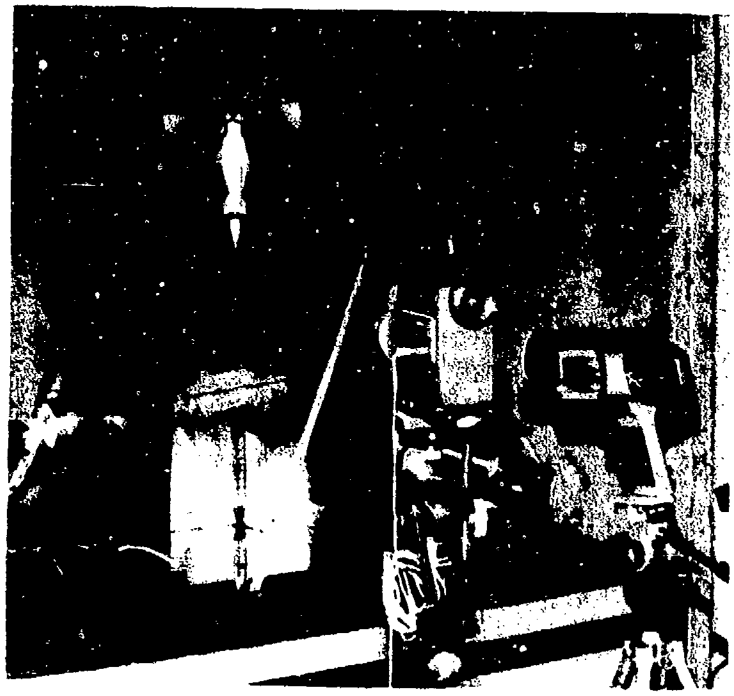

Figure 5. Hot manifold test apparatus, with an infrared thermometer for surface temperature measurement and a motion picture camera for recording the experiments.

Figure 6. Hot manifold ignition test with JP-4 under conditions of fluid stream delivery.

The relative position of the manifold with reference to the enclosure base can be varied from parallel to forming an angle of 7.1 degrees. The contact time of fluids with the manifold surface can be varied conveniently by adjusting the vertical position of the manifold at one end.

The air flow rates across the frontal opening of the enclosure for tests conducted from 1975 through 1977, are shown in the sketch below.

20 cm/sec		25.8 cm/sec
	25 cm/sec	
8.3 cm/sec		13.3 cm/sec

The indicated rates were determined at a time when the manifold was not heated. When the manifold was heated, the rate of air flow through the enclosure was increased. For example, when the manifold temperature was 927°C (1700°F), the air flow rate through the center of the frontal opening was 36.7 cm/sec.

The ventilation and pollution abatement systems were changed in the Monsanto Fire Safety Test Laboratory in the spring of 1978. The air flow rate in the hood that contains the manifold ignition test apparatus has been increased. However, it has not as yet been redetermined.

2. The Manifold

The 61 cm (24 in.) long manifold had been fabricated from 18-8 (Type 304) stainless steel. It is heated internally by means of a silicon carbide heater (Carborundum Company, Type AT 31 x 12 x 1), powered by a welding power supply of high current output. The length of the intensely heated segment of the silicon carbide rod is 30 cm (12 in.); the ends of the rod are much colder than the center.

A 25.4 cm (10 in.) long 18-8 stainless steel rod of 3.2 mm (0.125 in.) diameter had been welded onto the front side of the manifold. Its purpose is to extend the contact time between the fluid and the manifold.

A 10-gauge chromel-alumel thermocouple had been welded onto the back side of the manifold. The output of the thermocouple is indicated by a recorder.

3. Manifold Surface Temperature Measurement

The manifold fabricated for the Monsanto Fire Safety Test Laboratory had been equipped with a thermocouple made from large-diameter [10-gauge, 2.59 mm (0.102 in.) diameter] wire. This wire had been selected to minimize the effects of oxidation, leading to breakage, when exposed to flames. The heavy-gauge thermocouple served mainly as the continuous temperature monitoring device for the manifold. Conductive and convective heat losses from the sensing site through the large-diameter wire cause the registered temperature to be low. Therefore, the 10-gauge thermocouple was calibrated by four other types of temperature measurement devices:

(a) Infrared pyrometers (Models HSA-4E and HSA-6E from William Wahl Corporation).

(b) Optical pyrometer (Leeds and Northrup Company, Model 8632-C, disappearing wire type) for temperatures above 800°C (1472°F).

(c) Tempilstiks.

(d) 30-gauge thermocouple.

The use of infrared pyrometers requires knowledge of the emissivity of the surface whose temperature is being determined. Simultaneous measurements with Tempilstiks and one of the infrared pyrometers were used to determine the emissivity of the 304 stainless steel surface of the manifold after prolonged exposure to fluids and flames at high temperatures. For that purpose, the temperature readings of the infrared pyrometer were brought to coincide with the surface temperature values determined with Tempilstiks by adjusting its emissivity setting. With the manifold that had been used extensively for ignition testing at temperatures ranging to 927°C (1700°F), the emissivity setting of 0.75 provided coincidence between the two surface temperature measurement techniques. This emissivity value was used throughout the reported work in temperature measurements with the infrared pyrometer. It is in reasonable agreement with spectrally resolved emissivity values reported in the literature (8).

The correlation graph for temperatures recorded with the 10-gauge thermocouple, with those determined with the infrared and optical pyrometers is presented in Figure 7. This correlation is based on measurements conducted over a period of two years. The least squares correlation coefficient for a second degree equation relating to the two temperature data sets is 0.9955.

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(8) Y. S. Touloukian and C. Y. Ho, Editors, "Thermophysical Properties of Selected Aerospace Materials," Part 1, Thermal Radiation Properties, Purdue University, 1976.

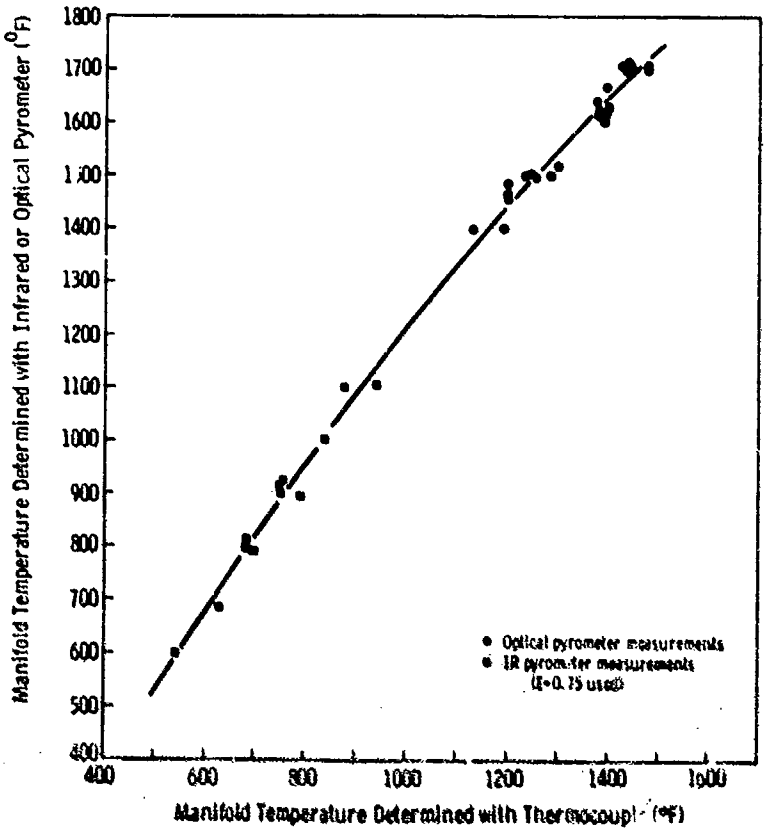

Figure 7. Correlation of hot manifold temperature measurements.

For one sequence of measurements, an auxiliary 30-gauge chromel-alumel thermocouple [0.25 mm (0.010 in.) wire diameter] was welded onto the surface of the manifold. It was attached at a distance of 1.90 cm (0.75 in.) from the 10-gauge thermocouple. Both thermocouples were in the same horizontal plane with reference to the long axis of the manifold.

Simultaneous temperature measurements were made with the two thermocouples, and with the infrared and optical pyrometer. The results of these measurements with a thermally equilibrated manifold are presented in Table 1 and Figure 8.

Conductive and convective heat transfer losses could cause the temperature measurements even with the 30-gauge thermocouple to be somewhat low. Most probably the correct surface temperatures are in the range defined by the 30-gauge thermocouple (T_1) as the lower limit and the infrared pyrometer (T_3) as the upper limit.

TABLE 1. HOT MANIFOLD TEMPERATURE CALIBRATION DATA

Power supply potential (volts)	Temperature (°F)				Temperature difference (°F)	
	30-gauge TC (T_1)	10-gauge TC (T_2)	IR pyrometer[a] (T_3)	Optical pyrometer (T_4)	T_1-T_2	T_3-T_1
	620	510	649		110	29
	725	602	763		123	38
	835	700	876		135	41
38.8	955	802	1015		153	60
44.5	1065	900	1094[b]		165	29[b]
51.5	1155	993	1198		163	43
59.9	1265	1098	1319		167	54
68	1360	1200	1427		160	67
78.5	1480	1308	1580		172	100
87	>1500	1372	1643	1621		

[a] Emissivity setting of 0.75 used.

[b] Infrared pyrometer switched to high-temperature range.

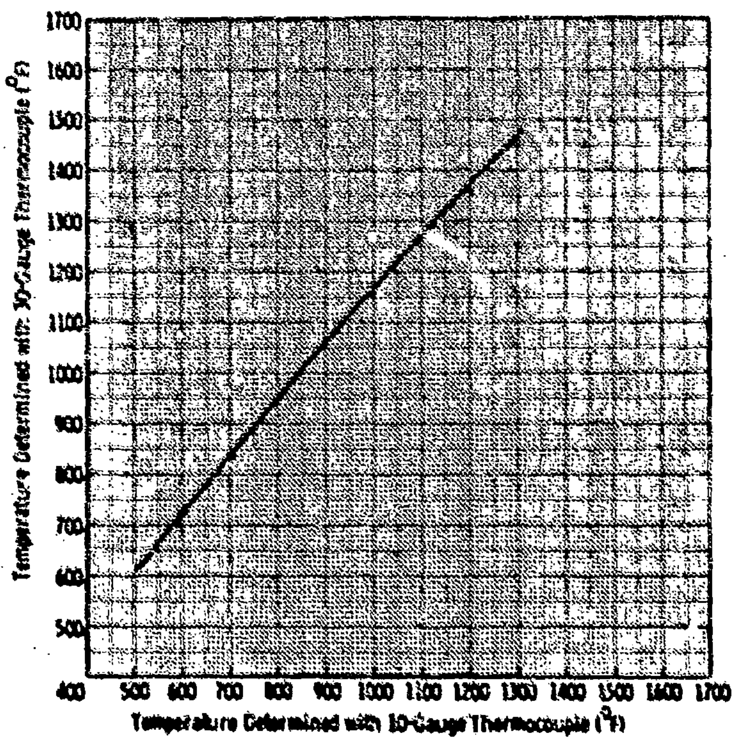

Figure 8. Correlation of hot manifold temperature measurement data for 10-gauge and 30-gauge chromel-alumel thermocouples.

It was of interest to determine some temperature profiles for the manifold surface, to develop a better appreciation of the thermal environment to which the fluids become exposed. A new manifold was fabricated for that purpose. It was dimensionally identical (7.62 cm OD x 0.11 cm wall x 61.0 cm long; 3 in. OD x 0.045 in. wall x 24 in. long) with the manifold that had been used at St. Charles for the determination of surface ignition temperatures of fluids. As was the old manifold, the new unit was also fabricated from Type 304 stainless steel.

Five 30-gauge chromel-alumel thermocouples were welded onto the surface of the manifold in the vertical center plane. Two additional identical thermocouples were welded onto the front side of the manifold. Three thermocouple lead wires were connected to a 12-position selector switch (Omega Engineering, Inc.). A recorder served as the temperature readout device.

The positions of thermocouple attachment to the manifold surface are indicated in Figure 9.

The manifold temperature profiles were determined at five different energy input rates into the heated system. These profiles are shown graphically in Figure 10. The temperatures ranged from 260°C to 688°C (500°F to 1270°F).

Under the selected equilibration conditions, temperature variations around the circumference in the center plane of the manifold ranged from 12°C to 33°C (25°F to 60°F). At low temperatures, the manifold was hottest on the top surface. At the highest power input, the bottom of the manifold was hotter than the other zones. At high manifold temperatures, reflection and emission of radiation by the enclosure walls cause heating of the bottom and back sides of the manifold.

The data in Figure 10 also indicate that the temperature at both ends of the 25 cm (10 in.) long "bead" is significantly lower than in the center of the manifold.

4. Fluid Delivery Devices

Burettes and beakers were used to deliver fluids in liquid stream form onto the manifold surface. By using burettes of three different sizes (10 ml, 25 ml, and 100 ml), different flow rates were produced. For example, with MIL-H-5606, the respective average flow rates were 0.35 ml/sec, 1.0 ml/sec, and 1.7 ml/sec.

Up to 25 ml of fluid was used per test when ignition did not occur. The entire 10-ml or 25-ml quantity was delivered onto the manifold surface while moving the burette tip parallel with the surface to minimize localized cooling. When ignition occurred, fluid delivery was stopped, unless it was of interest to observe the manner of burning and flame propagation.

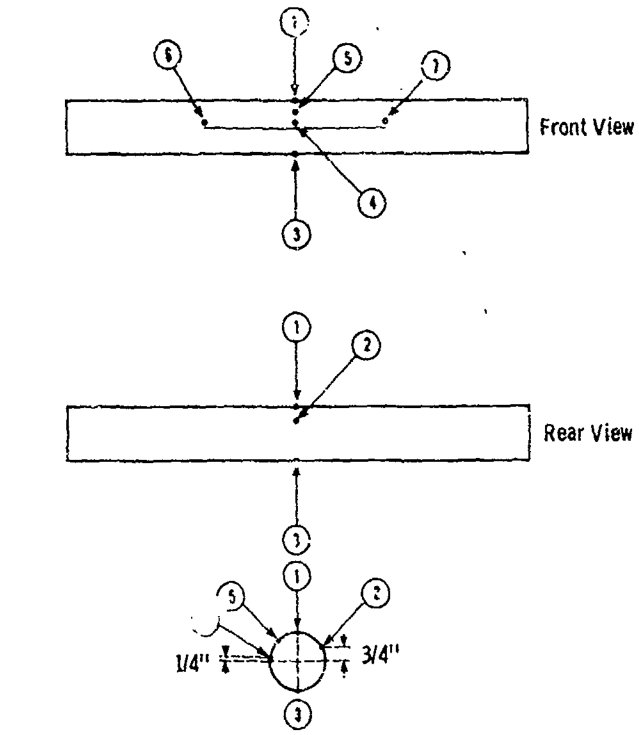

Figure 9. Positions of thermocouple attachment to the manifold surface.

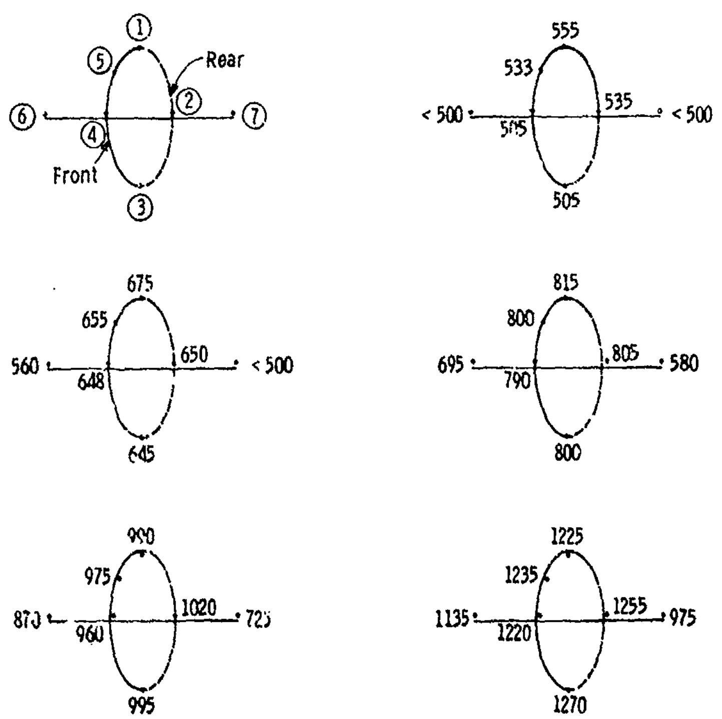

Figure 10. Temperature profiles of the hot manifold at different heat input rates.

Fluid (up to 50 ml) was delivered from a 100-ml beaker when delivery rates other than those attainable with burettes were desired.

The fluid delivery system for spray ignition tests consisted of a fluid container (3785 ml or 500 ml), equipped with piping and gauges for pressurization with nitrogen, and with an outlet tube for the fluids (see Figure 11). The steel container for the fluid was held in a supportive steel jacket. The latter was surrounded by a protective enclosure filled with sand. The entire spray generation system was supported on a mobile base. The test fluids were pressurized at 68 atm (1000 psi) with nitrogen.

During spray ignition tests with the propane torch, the fluid delivery valve was operated manually. During manifold spray ignition tests, 1-second bursts of fluid spray were provided by a solenoid-controlled valve that was actuated by a repeat cycle timer (Model CT530, A603 from Eagle Signals, Industrial Controls Division of Gulf and Western Industries, Inc.).

The following three spray nozzles were evaluated for the aerosolization of fluids in spray ignition tests:

- An Air Force 0.41 mm (0.016 in.) nozzle, with the swirl cone placed in the base position.
- Type 5000-Y1 nozzle from Spraying Systems Company.
- An oil burner type, hollow cone, 80-degree spray angle Factory Mutual nozzle (see Figure 12). It is rated at 1.5 gallons per hour, when used with 33 S.S.U.V. oil at 6.8 atm (100 psig). This nozzle was purchased from Hago Products, Inc., Mountainside, New Jersey.

The extent of atomization with the different nozzles was found to increase in the order as they are listed. The Air Force nozzle supplied a central stream of relatively large droplets. The spray pattern and the droplet size distribution can be varied with the Spraying Systems nozzle. The most uniform flow distribution within the spray cone and the most extensive dispersion of the liquid were attained with the Factory Mutual nozzle. The latter was selected as the preferred nozzle for the spray ignition system.

Preliminary experiments were conducted at pressures ranging from 150 to 1000 psi. Most stable flames were produced at the highest selected pressure. That pressure was subsequently used routinely for the spray ignition tests.

Figure 11. Pressurized fluid delivery system for spray ignition tests.

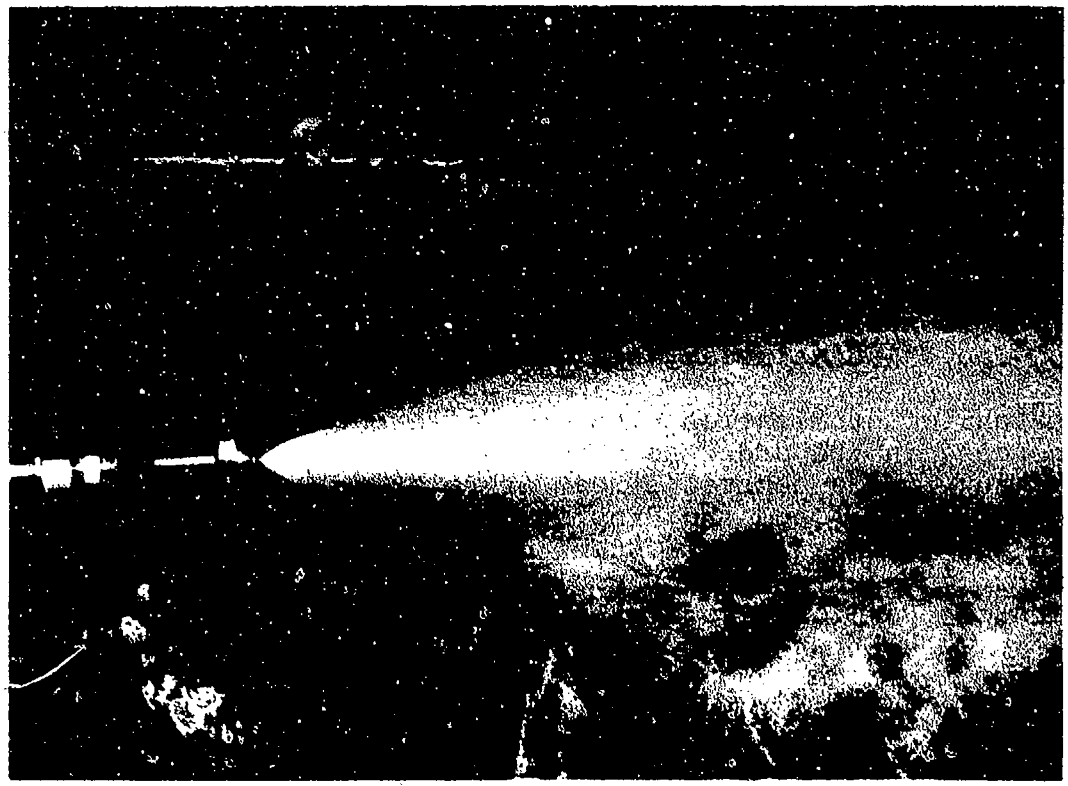

Figure 12. Spray pattern generated with the hydraulic fluid MIL-H-5606, using the Factory Mutual hollow cone nozzle.

B. Testing Procedures with the Manifold Test Apparatus

A number of experimental variables associated with the fluid delivery are influenced by the experimenter; these variables (e.g., rate of movement of the burette and the rate of fluid delivery onto the surface) are not precisely controllable with the present apparatus. Therefore, most experiments were conducted in triplicate.

The experimental procedure for manifold ignition tests was discussed extensively in conjunction with the apparatus.

In manifold spray ignition tests, the distance between the spray nozzle and the manifold surface was 7.2 cm. The spray was directed at the center of the manifold. The angle between the manifold major axis and the direction of the spray was 60 degrees (see Figures 13 and 14).

Most experiments were recorded for later reviewing with a Nikon Super-8 motion picture camera at a speed of 18 frames per second on Kodachrome 40 film, using automatic exposure control. Selected experiments have also been recorded on 16-mm motion picture film for the preparation of an AFWAL film clip. Additionally, still photographic coverage has been obtained of significant, observable burning characteristics of fluids.

IV. DESIGN AND FABRICATION OF A LABORATORY-SCALE HOT IGNITION TEST APPARATUS

The purpose for designing and fabricating the hot surface ignition test apparatus was to provide a small, laboratory-scale system for determining the ignitability of fluids under accident-simulative, controlled conditions.

The system consists of a heater assembly and a power supply (see Figures 15 and 16). The surface dimensions of the heating element are 10 cm x 25 cm (4 in. x 10 in.); its top surface is covered by a removable 16 cm x 29 cm (5.5 in. x 11.5 in.) plate. Kanthal A-1 wire, capable of operating at temperatures to 1316°C (2400°F), was used for the four separate, individually controllable heating elements. The heater was designed for a maximum power input of 3000 watts. It was built by Deltech, Inc., of Denver, Colorado.

The heater is mounted in a bracket that is fastened to a support frame. The angle of inclination of the bracket with reference to the base of the frame can be varied, to change the contact time of the fluid with the plate. Concomitantly, the extent of heating of the fluid and vapor concentration above the plate can be controlled.

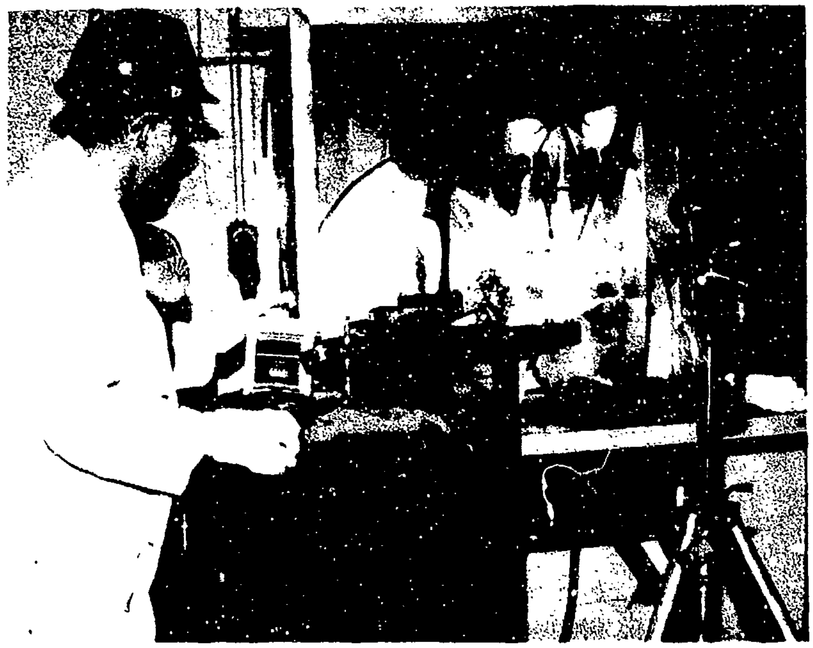

Figure 13. Ignition of JP-4 spray and flame propagation were continuously recorded with a motion picture camera.

Figure 14. Fluid (Skydrol® 500B) spray impingement onto hot manifold below the ignition temperature.

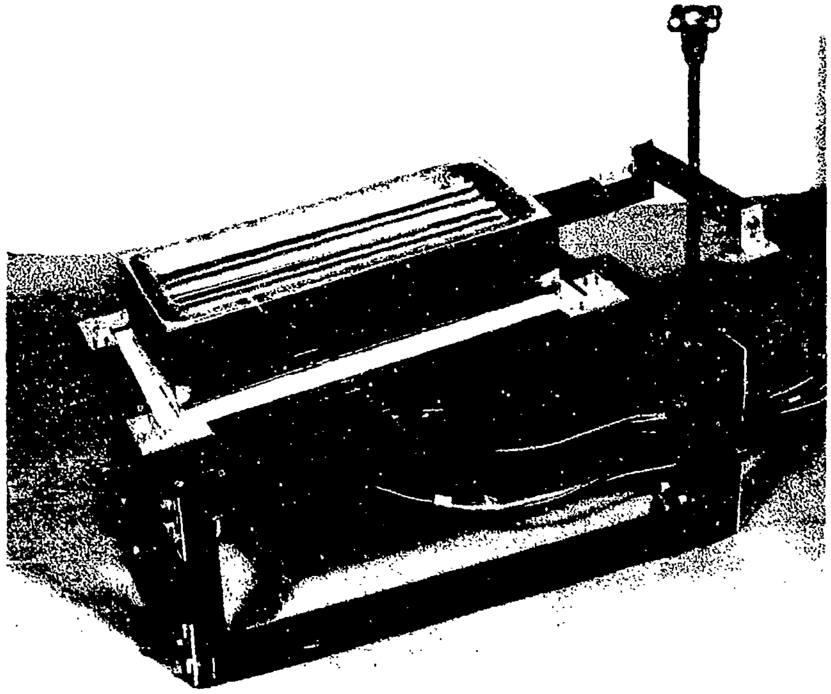

Figure 15. Heater assembly for the hot surface ignition test apparatus.

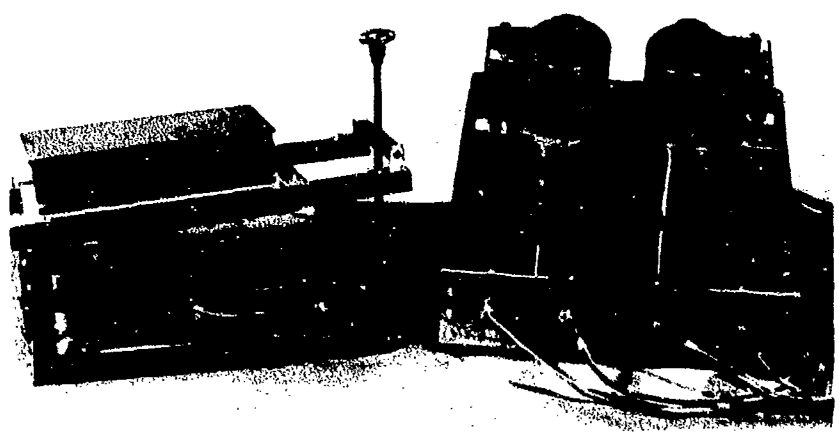

Figure 16. Hot surface ignition test apparatus.

The metal surface plate is not physically fastened to the heater assembly. It is planned to use plates of different compositions (e.g., Hastelloy Alloy X, stainless steels, titanium, aluminum alloys, and others) to determine the effect of metal composition and surface characteristics of the ignitability of fluids.

Power to the heater assembly is provided by four Powerstat variable autotransformers. Each of these provides up to 15 amperes output at 120 volts.

The apparatus has been test-operated. The desired surface temperature of 976°C (1700°F) is readily attainable at about two-thirds of the rated power input into the heater. While in operation with the upper plate surface at 977°C (1700°F), the heater surface had to be mantained at 1038°C (1900°F) to compensate for heat losses.

V. FLUID SPRAY IGNITION WITH PROPANE TORCH

The fluid containment and dispersal apparatus was identical with the apparatus used for spray ignition experiments with the hot manifold (see pp. 20 and 21). As a procedural difference, the durations of spray discharge were controlled manually and they were longer than the 1-sec pulses used for the hot manifold ignition experiments.

The aerosolized sprays were generated with an oil burner-type, hollow-cone, 80-degree spray angle Factory Mutual nozzle. Nitrogen pressure on the fluid was maintained at 68 atm (1000 psi). To evaluate the ignition and flame propagation characteristics of the aerosolized fluids, a propane torch was traversed through these sprays at distances of 0.15 m, 0.61 m, and 1.1 m (0.5 ft, 2 ft, and 3.5 ft) from the nozzle. Observations regarding the following ignition, flame propagation, and extinguishment characteristics were noted: Does the fluid ignite? Do the flames flash back toward the nozzle? Are the flames propagated downstream? Does burning continue or are the flames extinguished after removal of the torch?

RESULTS AND DISCUSSION

I. AIRCRAFT FLUIDS

The primary area of interest to the Air Force was the performance of the various hydraulic fluids under the set of conditions specified by Criteria B. The fluids were initially screened to determine the heats of combustion and the minimum autoignition temperatures. The fluids meeting the former requirement were considered for testing in the hot manifold test sequence at St. Charles, MO. For comparison purposes, the currently used military fluids and commercial airline fluids were subjected to identical tests. The current military fluids included MIL-H-5606, a mineral oil type, and MIL-H-83282, a synthetic hydrocarbon fluid. The former is the standard fluid of the Air Force. The commercial airline fluids, as represented by Skydrol® 500B, are the phosphate esters.

Most fluids used in this work were received from the Project Engineer. The following are the manufacturers of fluids identified by trade names: Brayco® 814Z, Bray Oil Company; Fluorinert FC-48, 3M Company; Freon® E6.5, Du Pont Company; Halocarbon® AO-8, Halocarbon Corporation; Skydrol® 500B and Coolanol® 25R, Monsanto Industrial Chemicals Company; Chevron M2V, Chevron Chemical Company.

Nadraul MS-6 is an experimental hydraulic fluid, supplied to the Project Engineer by the U.S. Navy.

As a chemically distinct class of compounds, the fluorocarbons exhibited the lowest propensity for ignition, flame propagation and heat release upon combustion. The prime candidate nonflammable fluids showing the most promise were identified as Halocarbon® AO-8, produced by Halocarbon Corporation, Freon® E6.5 by Du Pont Company, and Brayco® 814Z from Bray Oil Company. In addition to hydraulic fluid formulations, limited comparative testing was conducted on aircraft fuels, lubricants and heat transfer fluids.

II. MINIMUM AUTOIGNITION TEMPERATURES

The minimum autoignition temperature of a fluid defines the lowest temperature, at a specific pressure, at which a mixture of its vapor with air under liquid-vapor equilibrium conditions will ignite spontaneously in a uniformly heated container. The minimum AIT is thus a very important criterion in analyzing potential fire hazards associated with the uses of fluids. It represents a limiting low temperature value for the ignition of combustible vapors. For ignition to occur at the minimum AIT, that temperature must prevail in a sufficiently large volume of vapor to prevent quenching of the radical chain reactions; these reactions lead, in a progressively accelerating manner, to ignition. The minimum autoignition temperatures of various hydraulic fluids, lubricating oils, and fuels were measured. The results are presented in Figure 17 and in Table A-1 in the Appendix.

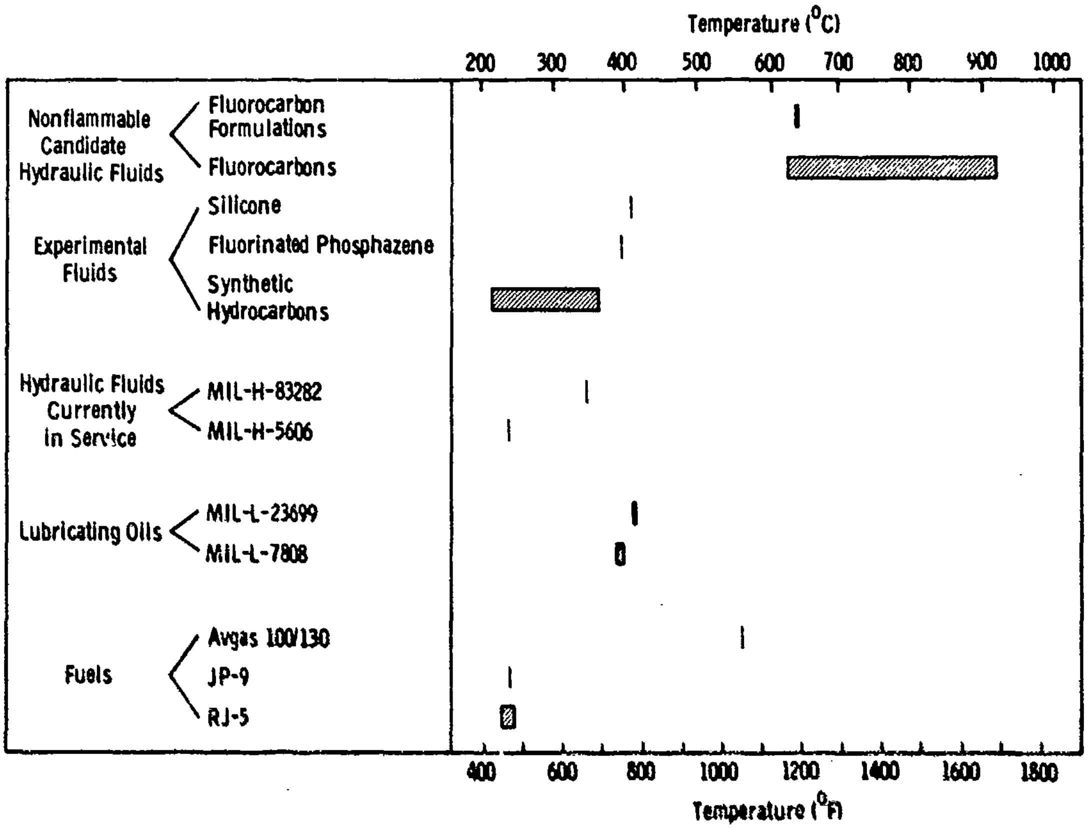

Figure 17. Autoignition temperature ranges of fluids by classes based on applications and chemical compositions.

As indicated in Figure 17, the minimum AIT's of the candidate fluids fall into three ranges:

- Hydrocarbons 216°C - 364°C (420°F - 690°F)
- Fluorinated phosphazene and silicone 395°C - 409°C (745°F - 770°F)
- Fluorocarbons 630°C - 917°C (1165°F - 1685°F).

The fluorocarbons have a remarkably low propensity for auto-ignition. The AIT's of the fluorocarbon fluids were found to be higher than the upper limit for the approximate minimum auto-ignition temperature [649°C (1200°F)] suggested for fluorocarbons in a recently published review (9). Two of the tested fluids (Krytox® and Brayco® 814Z) exceed the requirements of Advanced Hydraulic Fluid Flammability Criteria B (10), which stipulate a minimum AIT of 704°C (1300°F).

III. MEASUREMENT OF IGNITION DELAY TIMES WITH MIL-H-5606 AND MIL-H-83282

Measurements of the ignition delay times were conducted with samples of the same fluids that have been used for surface ignition experiments, utilizing the apparatus of ASTM Test D2155-66.

The ignition delay times observed with 0.1-ml samples, as functions of temperature, are presented in Table 2. The mineral oil-based hydraulic fluid, MIL-H-5606, exhibited a propensity for delayed ignition at temperatures ranging from 235°C - 316°C (455°F - 600°F) (see Figure 18). In contrast, the synthetic hydraulic fluid MIL-H-83282 exhibited a very abrupt change in susceptability to ignition at ~374°C (705°F); ignition with this fluid occurred with short delay times. Evidently, the activation energy of the ignition reaction of MIL-H-5606 is much lower than the corresponding value for MIL-H-83282.

Increasing the quantity of the fluid used for the test did not diminish the ignition temperature of MIL-H-5606; with MIL-H-83282, a significant reduction of the ignition temperature occurred when the quantity of the test sample was increased (see Table 3). Apparently, the latter fluid contains some more readily ignitable volatile components, whose concentrations in the vapor space of test flask are increased with increasing sample quantities.

The minimum autoignition temperatures of the hydraulic fluids determined in the present work agreed within 13°C (24°F) with previously reported values for fluids of identical designations (see footnotes to Table 3).

IV. HEATS OF COMBUSTION

The results of heat of combustion measurements are summarized in Figure 19, and in Table A-2 in the Appendix.

All fluorocarbons, the two fluorocarbon formulations, and the fluorinated phosphazenes were found to meet the requirement of

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(9) J. M. Kuchta, "Summary of Ignition Properties of Jet Fuels and Other Aircraft Combustible Fluids," AFAPL-TR-75-70, September 1975.

(10) Memo, B. P. Botteri to AFML/MBT (H. Schwenker), 13 November 1975.

TABLE 2. DELAY TIMES AS FUNCTIONS OF TEMPERATURE IN AUTOIGNITION TESTS WITH MIL-H-5606 AND MIL-H-83232[a]

Fluid	Temperature °C	Temperature °F	Ignition delay time (sec)
MIL-H-5606	316	600	1.7
	306	583	2.3
	296	564	3.5
	286	546	5.3
	275	527	7.7
	265	509	13.2
	255	491	35
	245	473	71
	238	461	161
	233	451	NI[b]
MIL-H-83282	399	750	<1
	381	717	2
	376	709	2
	372	701	NI[b]

[a]Measurements reported in this table were conducted with 0.10 ml samples of the fluids.

[b]No ignition in five minutes.

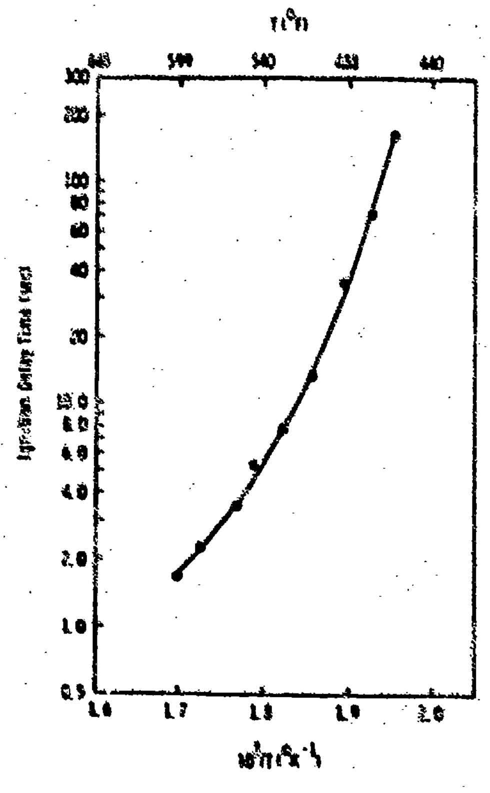

Figure 18. Ignition delay time for MIL-H-5606 as a function of temperature for ASTM Test D2155-66.

TABLE 3. EFFECT OF HYDRAULIC FLUID SAMPLE QUANTITY ON IGNITION TEMPERATURE

Fluid	Sample quantity (ml)	Temperature (°C)	Temperature (°F)	Ignition delay time (sec)
MIL-H-5606	0.01	238	461[a]	161
	0.20	239	462	NI[b]
MIL-H-83282	0.01	376	709	2
	0.20	370	698	<1
	0.30	>362	>683	
	0.50	347	656[c]	2

[a]Minimum autoignition temperature. Previously reported value 225°C (437°F) (9).

[b]No ignition.

[c]Minimum autoignition temperature. Previously reported value 354°C (670°F) (9).

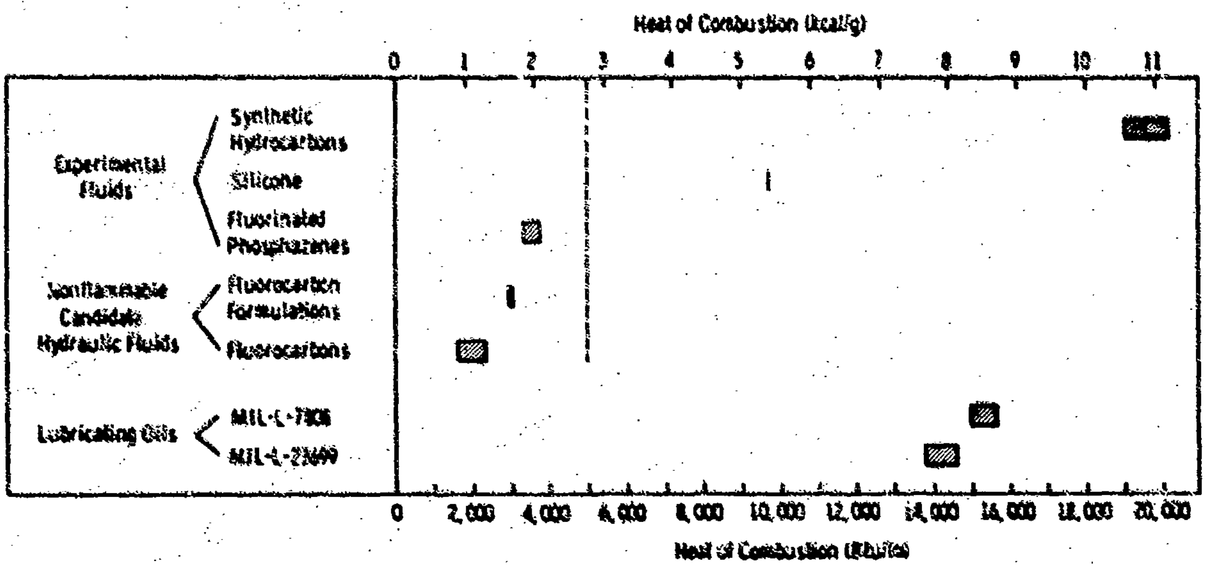

Figure 19. Heat of combustion ranges of fluids by classes, based on applications and chemical compositions.

Advanced Hydraulic Fluid Flammability Criteria B (10), which specify a heat of combustion value less than 2.78 kcal/g (5,000 Btu/lb).

The silicone fluid that was tested (Nadraul MS-6) and the experimental synthetic hydrocarbon fluids had heat of combustion values significantly above 2.78 kcal/g (5,000 Btu/lb).

V. IGNITION UPON IMPINGEMENT ONTO HOT MANIFOLD

The ignitabilities and ignition temperatures of various types of fluids upon impingement onto a hot manifold were determined. The measurements were conducted under conditions of liquid stream and spray impingement.

A. Hot Surface Ignition Characteristics of Presently Used Aircraft Hydraulic Fluids

The hot manifold ignition test results for the three currently used hydraulic fluids are summarized in Figure 20. Figures 33, and 34 in the Appendix depict the results for the several test sequences with MIL-H-5606 and MIL-H-83282 hydraulic fluids. Tables A-3 through A-7 contain the data for the tests with these fluids.

The fractional numbers indicate the number of ignitions with reference to the total number of tests, for experiments conducted at the indicated temperature. To facilitate overview of the data, the fractional numbers have been encircled for the test conditions that caused one or more ignitions.

1. Ignition of MIL-H-5605 upon Liquid Stream Impingement onto Hot Surface

During the initial testing of MIL-H-5606, its ignitability behavior upon impingement onto hot metal surfaces appeared erratic. However, a performance pattern became discernible upon completion of a parametric investigation of the ignitability behavior of this widely used fluid (see Figure 21).

The ignition temperature for MIL-H-5606, upon impingement onto the hot manifold surface, was found to be highly dependent upon the fluid flow rate. At different flow rates, the minimum ignition temperature ranged from 388°C (730°F) to 804°C (1480°F). The fluid flow rate affected the ignitability in the following manner:

- At the lowest selected fluid flow rate (~.35 ml/sec) ignition occurred at high temperatures. The lowest temperature at which ignition was observed was 804°C (1480°F).

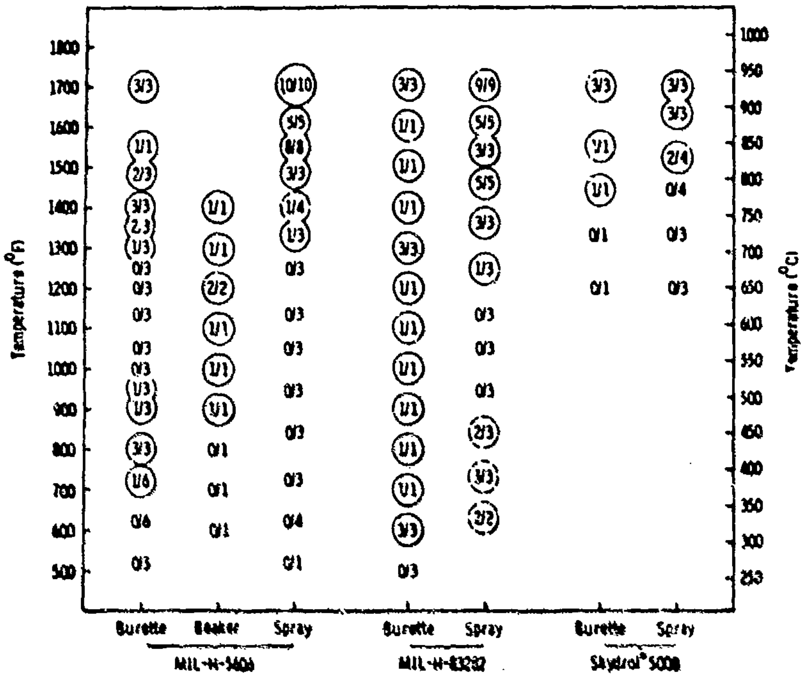

Figure 20. Summary of hot manifold ignition test results for MIL-H-5606, MIL-H-83232 and Skydrol® 500B. Liquid stream (≤25 ml) and spray impingement.

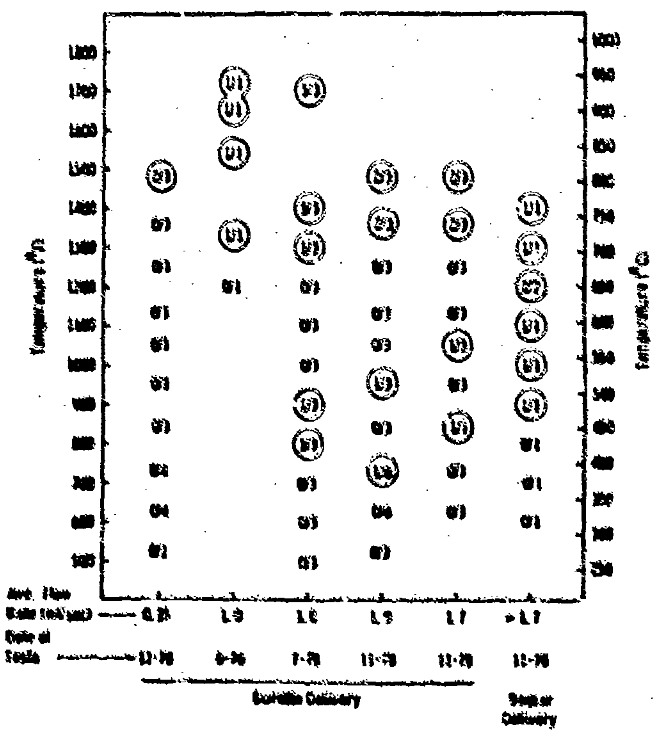

Figure 21. Ignitability of MIL-H-5606 upon liquid stream impingement onto the hot manifold, as a function of fluid flow rate.

- At the intermediate flow rates (~1 to 1.7 ml/sec, ignition was observed in two temperature regimes [388°C to 566°C (730°F to 1050°F), and at and above 704°C (1300°F)]. Ignition did not occur in the zone between these two regimes.

- At high fluid flow rates (>1.7 ml/sec), the lowest ignition temperature was 482°C (900°F). Ignition occurred at all temperatures above the minimum surface ignition temperature.

The following explanation is offered for the ignitability behavior of MIL-H-5606 upon impingement onto hot manifold surface (see Figure 21). At the slow flow rate of 0.35 ml/sec, a sufficiently high vapor concentration for ignition to occur was not generated until the manifold temperature reached 804°C (1480°F). At the highest flow rates used, with beaker delivery, sufficiently high vapor concentrations and temperatures are reached when the fluid was allowed to flow onto the manifold surface maintained at or above 482°C (900°F).

Ignition in two temperature regimes at intermediate fluid delivery rates is attributed to the combined effects of manifold surface temperature and geometry, and the physical properties of MIL-H-5606 fluid. At temperatures ranging from 260°C to 427°C (500°F to 800°F), the manifold surface was wetted extensively. As the manifold surface temperature was raised, the extents of vaporization and aerosol formation increased markedly. The lowest surface temperature at which ignition of fluid vapors occurred was 388°C (730°F).

Upon increase of the manifold temperature, the nonignition regime was reached. Less wetting of the surface was observed. Surface tension caused most of the fluid to flow over the curved surface as a liquid stream. Vapor and aerosol concentrations became lower and no ignition occurred.

Upon heating the manifold surface to still higher temperatures, sufficiently high vapor concentrations were generated to allow ignition to occur. However, a significant difference in burning pattern was observed in the two temperature ranges. At 388°C - 482°C (730°F - 900°F), very extensive burning of the fluid occurred on the manifold surface. At higher temperatures [T > 649° (1200°F)], most of the fluid flowed as a narrow liquid stream over the manifold surface (see Figure 22). Intermittent burning in the form of small flamelets was observed on the manifold surface. However, the bulk of the fluid burned with an intense flame in the tray below the manifold.

It should be noted that the ignition temperatures of MIL-H-5606 upon impingement onto hot manifold were significantly higher than the minimum AIT of that fluid [238°C (461°F)].

Figure 22. Poor surface wetting of the 760°C (1400°F) manifold surface by MIL-H-5606.

In conclusion it should also be noted that the repeatability of results obtained with the Manifold Ignition Test is not quantitative. The lack of quantitative repeatability is attributed mainly to the irreproducibility of human motions during the delivery of the fluid. It necessitates performing multiple tests under identical conditions, if the results are of significant interest. The results should be viewed in probabilistic terms.

2. Ignition of MIL-H-83282 upon Liquid Stream Impingement onto Hot Surface

Apparently the surface tension of MIL-H-83282 at high temperatures is lower than that of MIL-H-5606. Sufficient contact surface was developed between the former liquid and the manifold to attain adequate heat transfer to produce ignition of all temperatures above 316°C (600°F) (see Figure 20 and Table A-4). The extent of fluid burning on the manifold surface diminished with increasing temperature. The burning droplets occasionally propagated flames to the tray. However, because of the low vapor pressure of the fluid, the burning in the tray was only intermittent.

3. Ignitability of MIL-H-5605 - MIL-H-83282 Mixtures

Mixing of hydraulic fluids MIL-H-5606 and MIL-H-83282 may occur during the servicing of military aircraft. It was of interest for the Air Force to determine the ignitability characteristics of mixtures that could be formed through servicing of aircraft at Air Force and Navy air bases. Of particular interest was the effect of incorporating MIL-H-83282 as a minor component (up to 25 vol-%) in MIL-H-5606.

The data in Figure 23 and in Table A-5 indicate that low concentrations of MIL-H-83282 in MIL-H-5606 lower the ignition temperature of the latter fluid significantly. At a concentration of 5 vol-%, MIL-H-83282 lowers the ignition temperature of MIL-H-5606 approximately 72°C (130°F). In the concentration range of 5 vol-% to 100 vol-%, the manifold ignition temperature of the fluid compositions did not change detectably.

4. Ignition of Skydrol® 500B upon Liquid Stream Impingement onto Hot Surface

The lowest manifold temperature at which Skydrol® 500B ignited was 782°C (1440°F), significantly above the minimum AIT of 510°C (950°F). The flames were less intense than those formed in similar experiments with MIL-H-5606 and MIL-H-83282. A white aerosol was formed during the combustion of Skydrol® 500B. The burning droplets, falling from the hot manifold, extinguished in air. The flame never propagated to the fluid collected in the tray.

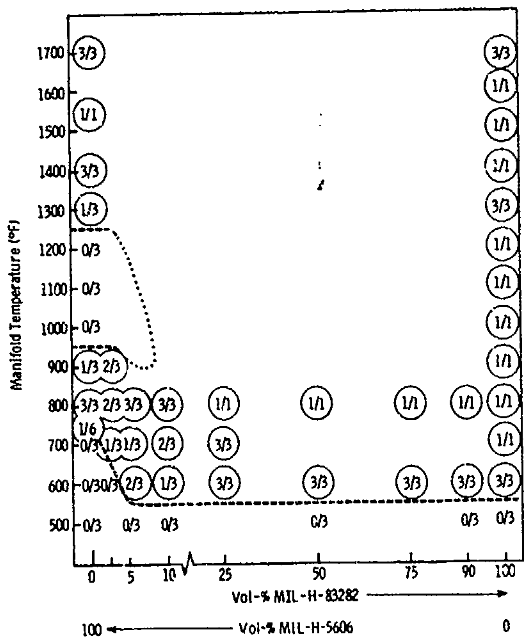

Figure 23. Ignition frequency of fluid compositions on hot manifold, with reference to the total number of tests, for the system MIL-H-5606 and MIL-H-38232.

5. Ignition of MIL-H-5606, MIL-H-83282, and Skydrol® 500B upon Spray Impingement onto A Hot Surface

The manifold surface was cooled significantly upon the impingement of high-pressure fluid sprays. Therefore, in comparison with fluid stream impingement, ignition occurred less readily. Consequently, the spray ignition temperatures of fluids were generally higher than the corresponding values for fluid stream impingement.

The results of spray ignition tests with the hydraulic fluids are incorporated in Figure 20; the experimental data are presented in Table A-7.

During some experiments, ignition on the manifold occurred after completion of the 1-second spray pulse. This type of ignition is indicated in Figure 20 by discontinuous circles around the fractional expressions that represent the ignition frequency.

MIL-H-5606 is a hydraulic fluid of relatively high vapor pressure. It vaporizes readily upon spray impingement onto the manifold. High surface temperatures are not required for vaporization to occur. The vapors remain relatively cool at low manifold temperatures, and they do not auto-ignite. The lowest manifold temperature at which ignition of MIL-H-5606 spray occurred was 721°C (1330°F), which is 333°C (600°F) above the manifold temperature at which this fluid ignited upon liquid stream delivery.

The hydraulic fluid MIL-H-83282 ignited during spray bursts at the manifold temperature of 677°C (1250°F). However, at manifold temperatures ranging from 332°C to 448°C (630°F to 840°F), sufficient quantities of fluid condensed onto the manifold to cause ignition after the 1-second spray bursts. Under the test condition used, no ignition occurred with MIL-H-83282 at manifold temperatures extending from 510°C to 654°C (950°F to 1210°F). In this temperature interval, most of the fluid was vaporized from the manifold surface during the spray bursts. Apparently, the vapor temperatures were not sufficiently high to induce autoignition.

The lowest manifold temperature at which autoignition of Skydrol® 500B spray occurred was 827°C (1520°F). For this fluid of high ignition temperature, the manifold temperature for spray ignition was only 44°C (80°F) higher than the corresponding temperature for fluid stream ignition.

6. Comparative Performance of MIL-H-5606 and MIL-H-83282 in Manifold Ignition Tests

Under the dynamic, accident-simulative conditions produced in the hot manifold ignition test in the absence of a flame or spark, the hydraulic fluid MIL-H-5606 ignited less readily than the fluid MIL-H-83282.

In fluid stream impingement experiments, the difference in minimum autoignition temperatures was 72°C (130°F) [388°C (730°F) vs 316°C (600°F)]. In spray ignition experiments, the fluid MIL-H-83282 exhibited a much greater propensity for ignition (see Figure 23). This was caused by the relatively lower vapor pressure of this fluid, causing condensation on the manifold, and subsequent vaporization and autoignition.

It should also be noted that under static thermal equilibration conditions, such as those prevailing in AIT measurements (2), the fluid MIL-H-5606 ignites at a lower temperature (238°C, 461°F) than MIL-H-83282 (347°C, 656°F).

The data in Figure 23, reviewed in conjunction of the minimum autoignition temperatures of the two hydraulic fluids, indicate how the relative safety in use varies, depending upon the conditions that would prevail in different accident situations.

B. Hot Surface Ignition Characteristics of Nonflammable and Experimental Hydraulic Fluids

1. Liquid Stream Impingement onto Hot Surface

The ignition test results for liquid stream impingement of candidate nonflammable fluids onto the hot manifold are summarized in Figure 24.

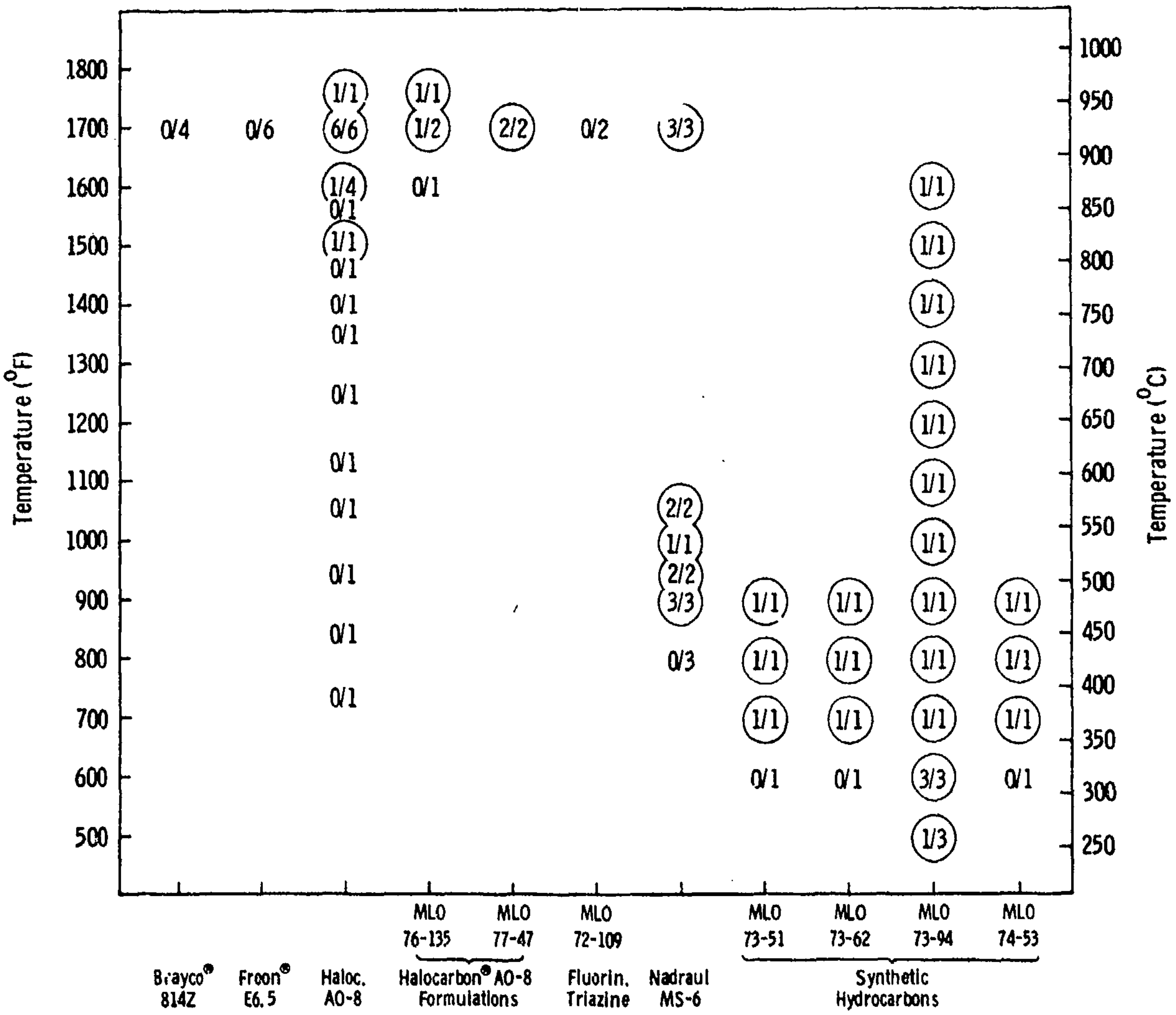

Figure 24. Summary of hot manifold ignition test results for candidate nonflammable and experimental hydraulic fluids with liquid stream impingement.

Some vertical data columns in Figure 24 are composite representations of two or more test sequences. The results for the individual test sequences, which provide an indication of repeatability, are shown in Figure 32 in the Appendix.

All ignition test results data for liquid stream impingement of candidate fluids are presented in Table A-8.

The fluoroalkyl ethers (Brayco® 814Z and Freon® E6.5) and the fluoroalkyl-substituted triazine (MLO 72-109) exhibited the lowest propensity for ignition among the fluids tested; these fluids did not ignite upon impinging onto the manifold heated to 927°C (1700°F).

The nonflammable candidate hydraulic fluid Halocarbon® AO-8 exhibited also low propensity for ignition. During three test sequences, the lowest manifold surface temperature at which ignition occurred was 927°C (1700°F); at another time, low-intensity flamelets were observed at 816°C (1500°F). In all instances when ignition occurred, the fluid burned only intermittently. The flames on the manifold were low. The droplets falling from the manifold did not propagate flames to the tray. All four of the above-described hydraulic fluids exhibited good fire resistance characteristics.

The formulations prepared from Halocarbon® AO-8 (MLO 76-35 and MLO 77-47) exhibited fire resistance by the presently used test that is identical with that of the base stock.

The candidate silicone hydraulic fluid, Nadraul MS-6, ignited on the manifold surface heated to 482°C (900°F). Burning droplets of this fluid propaged flames to the tray. Upon burning, the fluid left a residue on the manifold surface (see Figure 25). This residue sorbed fluid, causing prolonged burning. A white silica coating remained on the manifold after complete burning of the residue. The silicone fluid was found to burn with a very bright flame. Apparently the silicon-containing particles formed in the flame have very high emissivity in the visible spectral range.

The synthetic hydrocarbon-based candidate hydraulic fluids (MLO 73-51, MLO 73-62, MLO 73-94, and MLO 74-53) ignited in the 600°F to 700°F range similarly to MIL-H-83282. The fluid MLO 73-94 propagated flames more readily than MIL-H-83282. The burning droplets propaged the flames onto the tray, where the fluid continued to burn.

2. <u>Spray Impingement onto Hot Surface</u>

The hot manifold spray impingement tests results with the nonflammable candidate fluids are summarized in Figure 26. Additional details are presented in Table A-9.

None of the three halogenated fluids ignited in the 871°C to 927°C (1600°F to 1700°F) surface temperature range used for testing. The silicone fluid, in contrast, ignited on the surface heated to 588°C (1000°F). The surface temperature for spray ignition of the silicone fluid was 55°C (100°F) higher than during liquid stream impingement.

Figure 25. Manifold ignition test with Nadraul MS-6.

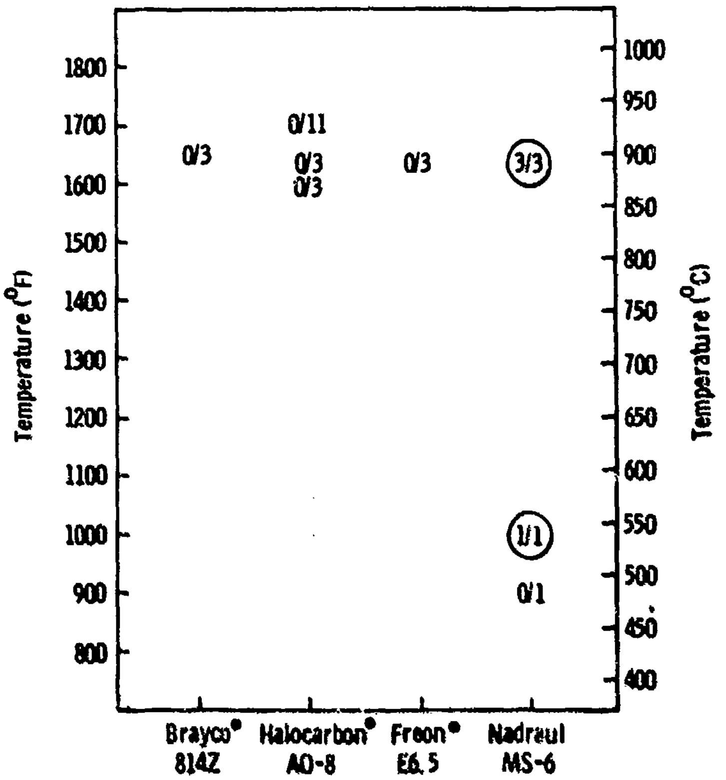

Figure 26. Hot manifold spray ignition test results with candidate nonflammable and experimental hydraulic fluids.

C. Hot Surface Ignition Characteristics of Jet Fuels

The hot manifold ignition temperatures were determined for six fuels under the conditions of fluid stream impingement. The results are presented in Figure 27 and in Table A-10. The ignition temperatures, in terms of the lowest manifold surface temperature at which ignition occurred, ranged from 593°C to 704°C (1100°F to 1700°F). These are approximately 454°C (850°F) higher than the lowest autoignition temperatures determined under the static vapor-liquid equilibrium conditions that prevail in the ASTM test designated D2155-66 (see Table A-1 and Ref. 9).

The relatively very high ignition temperatures of jet fuels upon impingement onto the hot manifold are attributed to very extensive vaporization at temperatures below those required for autoignition under thermal equilibrium conditions. The surface onto which the fluids impinge must be heated significantly above the minimum AIT to generate vapors of sufficiently high energy content to undergo ignition.

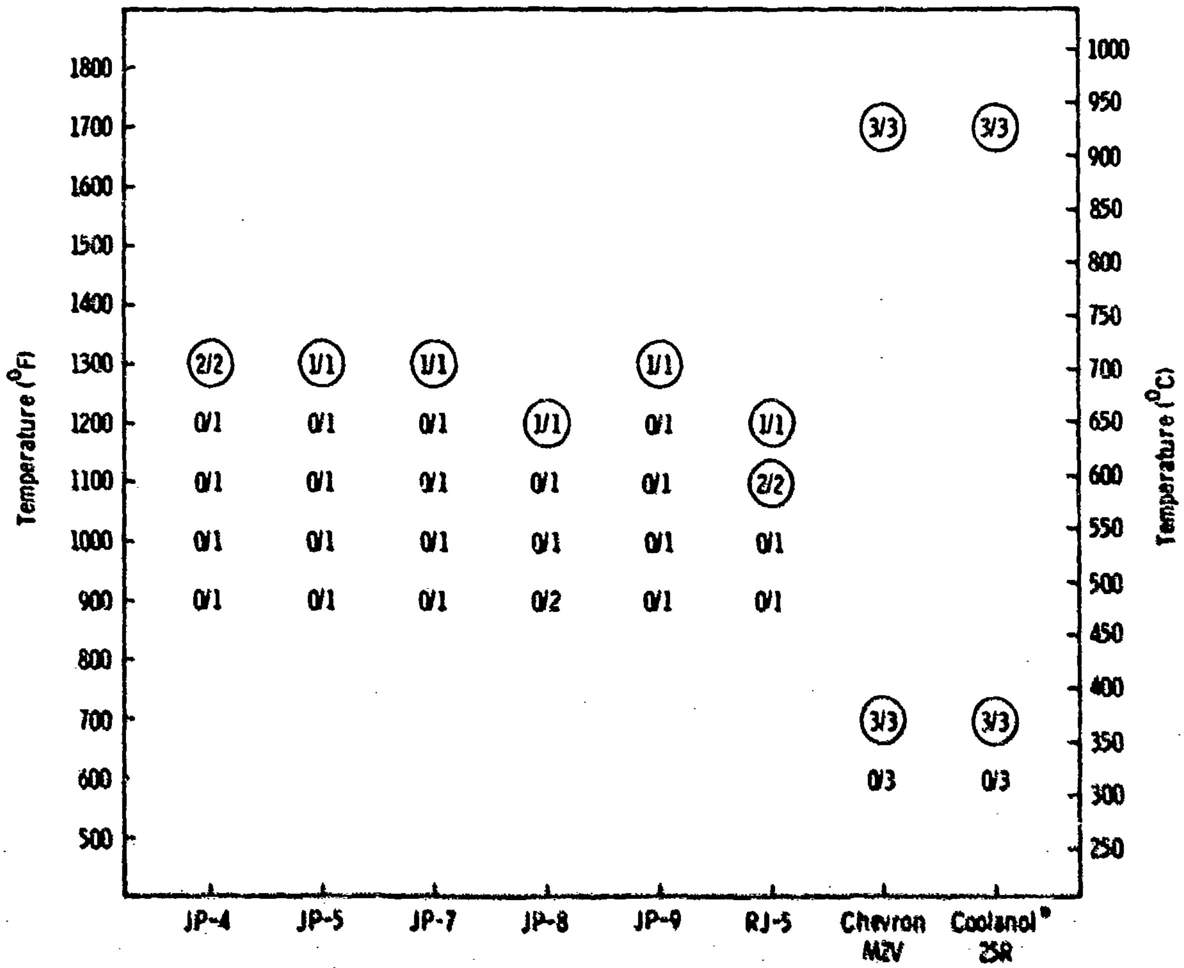

Figure 27. Hot manifold ignition test results for fuels and some other fluids with liquid stream impingement.

D. Hot Surface Ignition Characteristics of Other Fluids

The ignitability of a heat transfer fluid, Coolanol® 25R, and a commercial hydraulic fluid, Chevron M2V, was evaluated under conditions of fluid stream impingement onto the hot manifold. The results are presented in Figure 27 and in Table A-10.

The lowest manifold temperature at which the impinging fluids ignited was 371°C (700°F). The flames were more luminous than those developed upon burning of hydrocarbon fluids. The enhanced luminosity is associated with the presence of silicon, as discussed with reference to the silicone fluid Nadraul MS-6 on p. 38.

For reference, the minimum AIT of Chevron M2V has been reported (9) as 370°C (698°F).

E. Hot Surface Ignition Characteristics of Lubricating Oils

Hot surface ignition characteristics of two types of ester-based lubricating oils, MIL-L-7808 and MIL-L-23699, were investigated. Because of the high viscosity, these fluids were poured from beakers onto the manifold. The lowest manifold temperature at which oils of the former category ignited was 704°C (1300°F); the two polyester-type oils, MIL-L-23699, ignited at 593°C (1100°F) and 649°C (1200°F), respectively (see Figure 28 and Table A-11). The hot surface ignition temperatures are significantly higher than the AIT's of these fluids [398°C to 416°C (735°F to 780°F)] (11).

Very extensive vaporization of fluids occurred at temperatures below the surface ignition temperature, resulting presumably in the generation of vapors much cooler than the manifold surface. The two less volatile, MIL-L-23699 type lubricating oils ignited at somewhat lower temperatures than the more volatile fluids of the MIL-L-7808 type.

The spray ignition temperatures were found to be approximately 111°C (200°F) higher than the corresponding values for liquid stream delivery (see Figure 29 and Table A-12).

VI. IGNITION OF FLUID SPRAYS BY PROPANE TORCH

The ignition, flame propagation, and extinguishment characteristics of a number of aircraft fluid sprays, when exposed to a flame were determined. The results are summarized in Table 4.

The presently used hydrocarbon-based hydraulic fluids (MIL-H-5606 and MIL-H-83282) produced flashbacks and sustained combustion after removal of the torch (see Figure 30). In contrast, the phosphate ester type hydraulic fluid (Skydrol® 500B) propagated flames only downstream while its burning was supported by the propane torch. The flames extinguished upon removal of the ignition source.

Three candidate nonflammable fluids, Brayco® 814Z, Freon® E6.5 and Halocarbon® AO-8, were not ignited when the propane flame was traversed through the sprays. These fluids even had an inhibitory effect on the propane flame, enhancing its luminosity (see Figure 31).

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(11) J. M. Kuchta and R. J. Cato, "Review of Ignition and Flammability Properties of Lubricants," AFAPL-TR-67-126, January 1968.

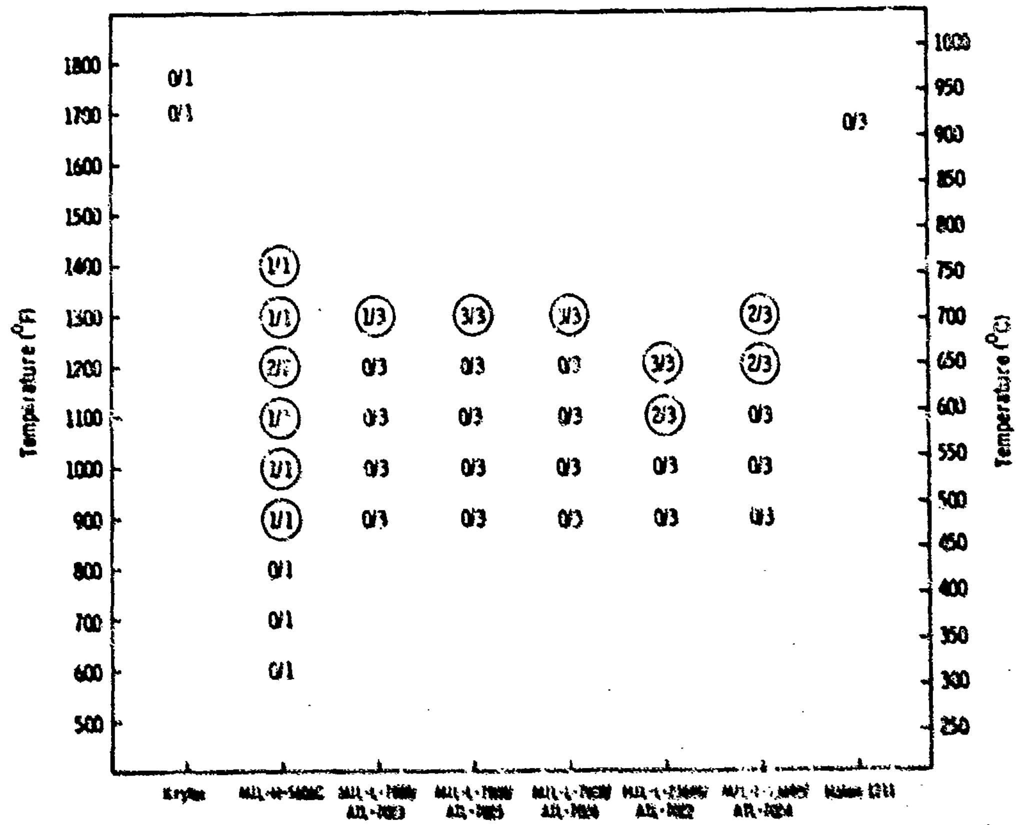

Figure 28. Hot manifold ignition test results for lubricating oils, Halon 1211, Krytox® and MIL-H-5606C. Beaker delivery.

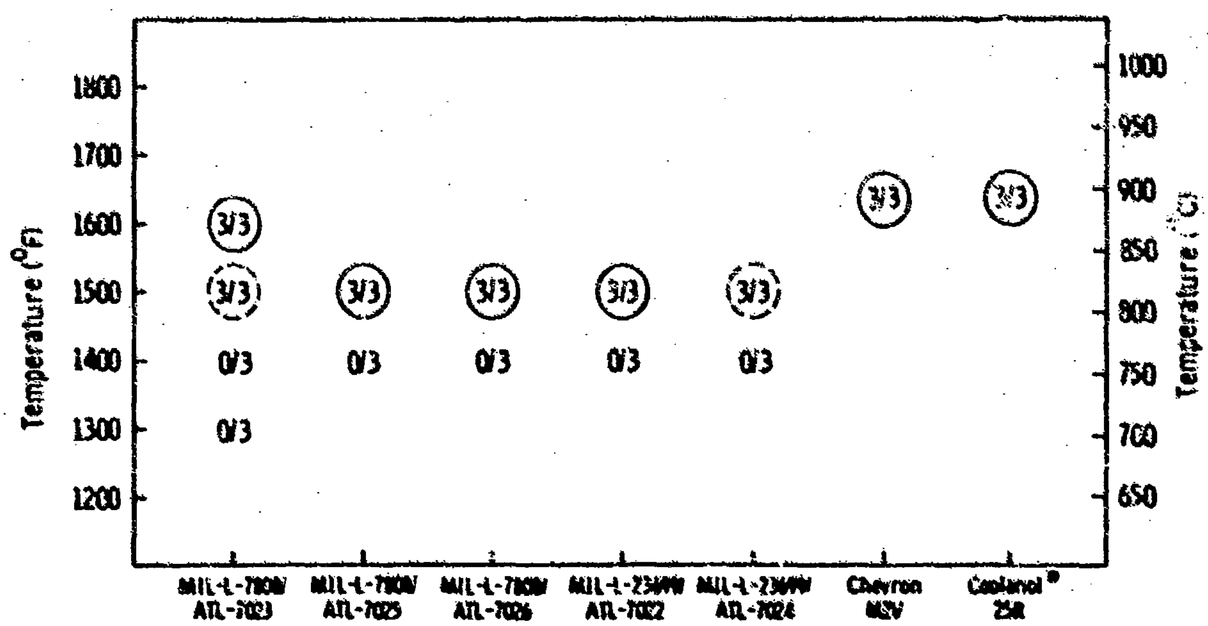

Figure 29. Hot manifold ignition test results for lubricating oils and silicate ester fluids. Spray impingement.

TABLE 4. RESULTS OF SPRAY IGNITION TESTS WITH PROPANE TORCH

Experiment number	Fluid type	Name	Air Force designation	Distance at which torch was introduced into the fluid spray (ft)	Ignition and flame propagation characteristics: No ignition	Flash-back	Flames propagated downstream	Combustion continued after removal of torch	Flames extinguished after removal of torch
1,2	Candidate hydraulic fluid	Brayco® 814Z	MLO 76-13a	0.5, 2.0, 3.5	✓✓✓				
3-5	"	Halocarbon® AO-8	MLO 76-74[a]	0.5, 2.0, 3.5	✓✓✓				
6,7	"	Freon® E6.5	MLO 77-19	0.5, 2.0, 3.5	✓✓✓				
8-10	Experimental hydraulic fluid	Monsanto MS-6	MLO 77-41	0.5		✓	✓✓✓	✓	✓✓
				2.0		✓	✓✓✓	✓	✓✓
				3.5			✓✓✓		✓✓✓
12-15	Hydraulic fluid currently in service		MIL-H-5606[b]	0.5, 2.0, 3.5		✓✓✓	✓✓✓	✓✓✓	
16-19	"		MIL-H-83282[c]	0.5, 2.0, 3.5		✓✓✓	✓✓✓	✓✓✓	
20-21	Hydraulic fluid	Skydrol® 500B		0.5, 2.0, 3.5			✓✓✓		✓✓✓
22	Lubricating oil		MIL-L-7808/ATL-7025	0.5		✓✓✓	✓✓✓	✓✓✓	
			"	2.0		✓✓✓	✓✓✓	✓✓✓	
			"	3.5			✓✓✓		✓✓✓
23	"		MIL-L-7808/ATL-7015	0.5		✓✓✓	✓✓✓	✓✓✓	
			"	2.0		✓✓✓	✓✓✓	✓✓✓	
			"	3.5			✓✓✓		✓✓✓
24	"		MIL-L-7808/ATL-7026	0.5		✓✓✓	✓✓✓	✓✓✓	
			"	2.0		✓✓	✓✓✓	✓✓	✓
			"	3.5			✓✓✓		✓✓✓
25	"		MIL-L-23699/ATL-7022	0.5		✓✓✓	✓✓✓	✓✓✓	
			"	2.0		✓	✓✓✓	✓	✓✓
			"	3.5			✓✓✓		✓✓✓
26	"		MIL-L-23699/ATL-7024	0.5		✓✓✓	✓✓✓	✓✓✓	
			"	2.0		✓	✓✓✓	✓	✓✓
			"	3.5			✓✓✓		✓✓✓
27,28	Hydraulic transfer fluid	Chevron MSV	MLO 75-14	0.5, 2.0, 3.5		✓✓✓	✓✓✓	✓✓✓	
29	Heat transfer fluid	Coolanol® 25R		0.5, 2.0, 3.5		✓✓✓	✓✓✓	✓✓✓	

[a] A sample of Halocarbon® AO-8, designated as MLO 77-64, was also used.

[b] Samples designated MIL-H-5606A, MIL-H-5606C and MIL-H-5606B exhibited identical behavior under the conditions of this test.

[c] A sample designated MIL-H-83282A exhibited identical behavior under the conditions of this test.

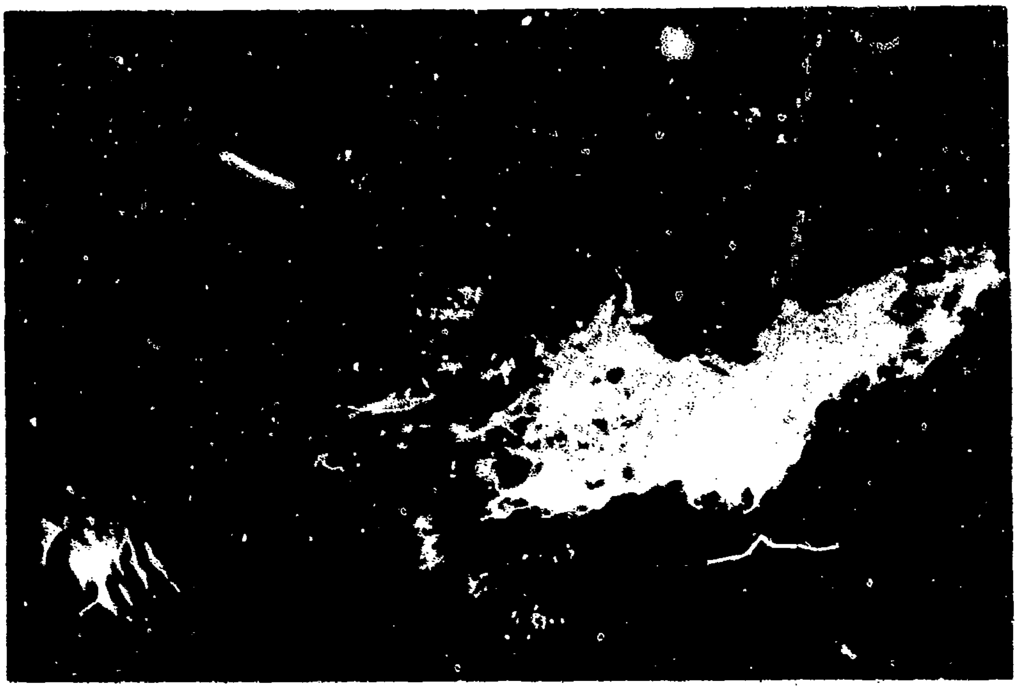

Figure 30. Propagation of flames by MIL-H-5606 fluid spray.

Figure 31. Attempted ignition of Halocarbon® AO-8 fluid spray with propane torch.

In contrast, the silicone-type experimental hydraulic fluid Nadraul MS-6 ignited and always propagated flames downstream. During two tests, involving traversal of the torch through the sprays at distances of 15 cm (6 in.) and 61 cm (2 ft), flame flashbacks occurred. The flames propagated upstream along the spray path to a distance of approximately 8 cm (3 in.) from the nozzle. During those two tests, the flames were sustained after removal of the torch. When the propane torch was traversed through the silicone fluid spray 107 cm (3.5 ft) from the nozzle, the flames extinguished upon removal of the torch.

The flame propagation pattern experienced with the silicone-type hydraulic fluid was generally encountered with other flammable fluids. If the fluid was flammable and present at sufficiently high concentration, flashback to the proximity of nozzle occurred. The flames were self-supporting and the fluid continued to burn after the torch was removed. Conversely, with less flammable fluids, the flames propagated only downstream from the propane torch, and they were not sustained after removal of the torch.

The aliphatic ester-type lubricating oils exhibited flame propagation characteristics intermediate between those of hydrocarbon and phosphate ester-type hydraulic fluids. When the torch was introduced into the spray close to the dispersion nozzle (15 cm, 6 in.), the flames always flashed back and burning was sustained after removal of the ignition source. When the torch was traversed through the spray at the intermediate distance (51 cm, 24 in.), flashback occurred in most instances with MIL-L-7808. MIL-L-23699 exhibited a somewhat lower propensity for flame propagation, and flashbacks occurred with a lesser frequency than with the former lubricating oils. Finally, when the propane torch was traversed through the oil spray at the distance of 107 cm (3.5 ft), flames propagated only downstream and extinguished upon removal of the ignition source.

The two silicate ester type fluids tested in this program, Chevron M2V and Coolanol® 25R, were found to behave similarly both in hot surface ignition, and in propane flame ignition and flame propagation characteristics. Both fluids were ignited by the torch. Flashback to the dispersion nozzle occurred at all three distances at which the propane torch was traversed through the spray. In all instances, the fluid sprays continued to burn after removal of the torch.

VII. SUMMARY OF HEAT OF COMBUSTION AND IGNITION DATA

The heat of combustion and the minimum ignition temperature data are summarized in Table 5 to facilitate an overview and to provide ready access. The minimum ignition temperature data include those for ignition in a uniformly heated volume and for surface-ignition upon liquid stream and spray impingement. The reader may wish to use Table 5 in conjunction with Table 4. The latter contains a summary of ignition characteristics of fluids upon exposure to flames, and of flame propagation properties of fluid sprays.

Replicate data, arising from duplication of tests with some fluids, were deleted in assembling Table 5. For any composition for which more than one test or test sequence was conducted, Table 5 contains the highest heat of combustion value and the lowest ignition temperature value measured in this program.

TABLE 5. SUMMARY OF MINIMUM IGNITION TEMPERATURE AND HEAT OF COMBUSTION DATA

Fluid: Chemical class	Fluid: Trade name	Fluid: Air Force designation	Heat combustion (kcal/g)	Heat combustion (Btu/lb)	Minimum ignition temperature (°C): AIT	Minimum ignition temperature (°C): Manifold: Liquid stream	Minimum ignition temperature (°C): Manifold: Spray	Minimum ignition temperature (°F): AIT	Minimum ignition temperature (°F): Manifold: Liquid stream	Minimum ignition temperature (°F): Manifold: Spray
Candidate Hydraulic Fluids										
Fluoroalkyl ether	Brayco® 814Z		1.650[a]	2,970[a]	917	>927	>893	1,685	>1,700	>1,640
"	Fluorinert FC-48		(1.250[a,b])	(2,250[a,b])						
"	Freon® E6.5		0.989[a]	1,780[a]	669	>927	>888	1,235	>1,700	>1,630
Fluoroalkyl ether-substituted triazine		MLO 72-109				>927			>1,700	
" " "	Krytox®				833	>966		1,530	>1,770	
Fluorinated phosphazene		MLO 76-37	1.861[a]	3,350[a]						
"		MLO 76-38	2.100[a]	3,780[a]						
"		MLO 77-72	1.900[a]	3,420[a]	395			745		
Halocarbon	Halocarbon® AO-8		1.328[a]	2,390[a]	630	816	>927	1,165	1,500	>1,700
Halocarbon[c]			1.683[a]	3,030[a]	640			1,185		
Silicone	Nadraul MS-6		5.411	9,760	409	477	538	770	890	1,000
Hydrocarbon		MLO 73-51	10.578	19,640	216	371		420	700	
"		MLO 73-62	11.083	19,950	221	371		430	700	
"		MLO 73-94				≤260			≤500	
"		MLO 74-53	10.817	19,470	231	371		450	700	
"		MLO 77-121	11.228	20,210	218			425		
"		MLO 77-122	11.006	19,810	315			600		
"		MLO 77-124	11.183	20,130	315			600		
"		MLO 77-125	11.144	20,060	321			610		
"		MLO 77-142			364			690		
Proprietary composition		MLO 76-108	8.439	15,190	256			495		
"		MLO 77-114A	10.689	19,240						
"		MLO 77-114B	10.706	19,270						
"		MLO 77-114C	10.683	19,230						
"		MLO 77-123	10.483	18,870	321			610		
"		MLO 77-134	7.089	12,760	396			745		
"		MLO 77-135	7.117	12,810	406			765		

(continued)

TABLE 5 (continued)

Fluid: Chemical class	Fluid: Trade name	Fluid: Air Force designation	Heat combustion (kcal/g)	Heat combustion (Btu/lb)	Minimum ignition temperature (°C): AIT	Minimum ignition temperature (°C): Manifold Liquid stream	Minimum ignition temperature (°C): Manifold Spray	Minimum ignition temperature (°F): AIT	Minimum ignition temperature (°F): Manifold Liquid stream	Minimum ignition temperature (°F): Manifold Spray
<u>Hydraulic Fluids Currently in Service</u>										
Mineral oil-based hydrocarbon		MIL-H-5606	10.133[d]	18,240[d]	238	388	721	461	730	1,330
Synthetic hydrocarbon		MIL-H-83282	9.928[d]	17,870[d]	347	322	677	656	630	1,250
Phosphate ester	Skydrol® 500B		7.056[e]	12,700[e]	510	782	816	950	1,440	1,500
Silicate ester	Chevron M2V		8.162	14,690		371			700	
<u>Lubricating Oils</u>										
Aliphatic ester		MIL-L-7808/ATL-7023	8.344	15,020	399	704	871	750	1,300	1,600
"		MIL-L-7808/ATL-7025	8.728	15,710	399	704	816	750	1,300	1,500
"		MIL-L-7808/ATL-7026	8.567	15,420	391	704	816	735	1,300	1,500
"		MIL-L-23699/ATL-7022	8.139	14,650	413	593	816	775	1,100	1,500
"		MIL-L-23699/ATL-7024	7.656	13,780	416	649	>816	780	1,200	>1,500
<u>Fuels</u>										
Hydrocarbon		JP-4				704			1,300	
"		JP-5				704			1,300	
"		JP-7				704			1,300	
"		JP-8				649			1,200	
"		JP-9			240	704		465	1,300	
"		RJ-5			229	593		445	1,100	
	AvGas				565			1,050		
<u>Heat Transfer Fluid</u>										
Silicate ester	Coolanol® 25R		8.744	15,740		371			700	
<u>Fire Extinguishing Agent</u>										
	Halon 1211					>916			>1,680	

[a] To enhance ignitability and completeness of combustion, benzoic acid was incorporated into the fluid samples. The heat of combustion data were corrected for the quantities of incorporated benzoic acid, presuming that it burned completely.

[b] The combustion was very incomplete, even in the presence of benzoic acid. The measured heat of combustion value is not considered reliable.

[c] Formulation.

[d] Ref. 9.

[e] Data supplied by L. R. Stark, Monsanto Industrial Chemicals Company.

CONCLUSIONS

The relative ignition properties of the two hydraulic fluids currently used extensively for military aircraft, namely, MIL-H-5606 fluid and MIL-H-83282 fluid, were found to depend upon the exposure conditions that led to ignition. It was found that upon impingement of a liquid stream onto the surface of a hot manifold, MIL-H-83282 fluid had a lower minimum ignition temperature (322°C, 630°F) than MIL-H-5606 fluid (388°C, 730°F). Also, upon impingement of an aerosolized liquid spray onto the hot manifold, MIL-H-83282 fluid was found to ignite at a lower manifold temperature (677°C, 1250°F) than MIL-H-5606 fluid (721°C, 1330°F). However, in autoignition tests in which the samples were introduced into a uniformly heated volume, MIL-H-5606 fluid ignited at a lower temperature (238°C, 461°F) than MIL-H-83282 fluid (347°C, 656°F). The volatility, surface tension, and thermo-oxidation kinetics of the fluids are the major factors that affect their ignitability under different exposure conditions. Thus, the relative safety in use for the two liquids varies, depending upon the conditions that prevail in different unplanned leakage or spillage situations.

Burning droplets of MIL-H-83282 fluid, dripping from a hot manifold, were found to propagate flames less readily than those of MIL-H-5606 fluid. The higher vapor pressure of the latter fluid is a major factor contributing to the observed differences in flame propagation properties of falling droplets.

In terms of aerosolized spray ignition and flame propagation test results, both hydraulic fluids performed indistinguishably.

Among the chemically different types of candidate hydraulic fluids, the organic compounds of high fluorine content (ethers and chlorofluorocarbons) exhibited the optimum combination of desirable fire performance properties. This includes a high ignition temperature, low propensity to propagate flames, and a low heat of combustion. There are nonflammable candidates that either meet or approach the requirements of Flammability Criteria B for Air Force Advanced Hydraulic Fluids. These fluids were identified as Halocarbon® AO-8, Freon® E6.5, and Brayco® 814Z.

RECOMMENDATIONS

This program has been successful in the establishment of testing capability and evaluation of the hydraulic fluids for the minimum (Class B) Air Force criteria (927°C, 1700°F). However, additional efforts are required to extend the testing capabilities to the maximum (Class A), that is to 1649°C (3000°F). Therefore, the following is recommended.

a. A surface ignition apparatus, capable of operating at temperatures up to 1649°C (3000°F), should be designed and fabricated. This apparatus would be simulative of the carbon brake assemblies of advanced aircraft, such as the F-16. It would be used to determine the hot surface ignition characteristics of the candidate nonflammable hydraulic fluids at high temperatures.

b. Studies should be pursued to investigate the effects of initial injection pressure on the ignition characteristics of hydraulic fluids. An apparatus should be designed and constructed for simulating pressurized leaks from current (3000 psi) and future (8000 psi) hydraulic systems.

c. Studies should be pursued to determine the effects of metallurgy on the flammability characteristics of hydraulic fluids. The small scale laboratory unit developed under this program should be modified to incorporate different metals, such as titanium and Inconel alloys. The surface geometry should be modified to ensure maximum contact time with the fluids.

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10. Memo, B. P. Botteri to AFML/MBT (H. Schwenker), 13 November 1975.

11. J. M. Kuchta and R. J. Cato, "Review of Ignition and Flammability Properties of Lubricants," AFAPL-TR-67-126, January 1968.

APPENDIX

TABULATIONS OF EXPERIMENTAL DATA

The following abbreviations and symbols are used in Tables A-1 through A-12 and Figures 32-35:

II - immediate ignition

BDI - briefly delayed ignition (less than 1 sec after fluid impinged onto the manifold)

DI( ) - delayed ignition, in ( ) sec after fluid impinged onto the manifold

IAS - ignition after spraying

TI - transitory ignition

○ - ignition occurred during fluid impingement in one or more hot manifold test under the indicated conditions

◌ - ignition occurred after spray impinagement during one or more hot manifold test under the indicated conditions.

TABLE A-1. AUTOIGNITION TEMPERATURES OF FLUIDS

No.	Fluid type	Chemical class	Name	Air Force designation	AIT °C	AIT °F	Remarks
1	Experimental hydraulic fluid	Synthetic hydrocarbon		MLO 73-51	216	420	
2	"	"		MLO 73-62	221	430	
3	"	"		MLO 74-53	231	450	
4	"	"		MLO 77-121	218	425	
5	"	"		MLO 77-122	315	600	
6	"	"		MLO 77-124	315	600	
7	"	"		MLO 77-125	321	610	
8	"	"		MLO 77-142	364	690	
9	Candidate hydraulic fluid	Fluorocarbon	Halocarbon® AO-8	MLO 76-74	643	1190	
10	"	"	"	MLO 76-122	630	1165	
11	"	"	"	MLO 76-135	640	1185	Formulation
12	"	"	"	MLO 77-47	642	1190	"
13	Experimental hydraulic fluid	"	Krytox®	MLO 76-73	833	1530	
14	Candidate hydraulic fluid	"	Brayco® 814Z	MLO 76-107	917	1685	
15	"	"	Freon® E6.5	MLO 76-119	669	1235	
16	Experimental hydraulic fluid	Fluorinated phosphazene		MLO 77-72	395	745	
17	"	Silicone	Nadraul MS-6	MLO 77-41	409	770	
18	"	Proprietary composition		MLO 76-108	256	495	
19	"	" "		MLO 77-123	321	610	
20	"	" "		MLO 77-134	396	745	
21	"	" "		MLO 77-135	406	765	
22	Hydraulic fluid, currently in service	Mineral oil-based hydrocarbon		MIL-H-5606	238	461	
23	"	Synthetic hydrocarbon		MIL-H-83282	347	656	
24	Fuel	Hydrocarbon	AvGas 100/130		565	1050	
25	"	"		JP-9	240	465	
26	"	"		RJ-5	246	475	
27	"	"		RJ-5	229	445	
28	Lubricating oil			MIL-L-7808/ATL-7023	399	750	
29	"			MIL-L-7808/ATL-7025	399	750	
30	"			MIL-L-7808/ATL-7026	391	735	
31	"			MIL-L-23699/ATL-7022	413	775	
32	"			MIL-L-23699/ATL-7024	416	780	

TABLE A-2. HEATS OF COMBUSTION OF FLUIDS

No.	Fluid type	Chemical class	Name	Air Force designation	ΔH_{comb} kcal/g	ΔH_{comb} Btu/lb	Remarks
1	Experimental hydraulic fluid	Synthetic hydrocarbon		MLO 73-51	10.578	19,040	
2	"	"		MLO 73-62	11.083	19,950	
3	"	"		MLO 74-53	10.817	19,470	
4	"	"		MLO 77-121	11.228	20,210	
5	"	"		MLO 77-122	11.006	19,810	
6	"	"		MLO 77-124	11.183	20,130	
7	"	"		MLO 77-125	11.144	20,060	
8	Candidate hydraulic fluid	Fluorocarbon	Halocarbon® AO-8	MLO 76-29[a]	1.261	2,270	
9	"	"	"	MLO 76-74[a]	1.250	2,250	
10	"	"	"	MLO 76-122[a]	1.328	2,390	
11	"	"	"	MLO 76-135[a]	1.683	3,030	Formulation
12	"	"	"	MLO 77-47[a]	1.650	2,970	"
13	Experimental hydraulic fluid	"	Krytox®	MLO 76-73[a]	0.911	1,640	
14	"	"	FC-48 (Fluorinert)	MLO 76-91	1.250	2,250	
15	Candidate hydraulic fluid	"	Brayco® 814Z	MLO 76-107[a]	(0.134)	(241)[b]	
16	"	"	Freon® E6.5	MLO 76-119[a]	0.989	1,780	
17	Experimental hydraulic fluid	Fluorinated phosphazene		MLO 76-37[a]	1.861	3,350	
18	"	"		MLO 76-38[a]	2.100	3,780	
19	"	"		MLO 77-72[a]	1.900	3,420	
20	"	Silicone	Hadraul MS-6	MLO 77-41	5.411	9,740	
21	"	"	Hadraul MS-6[c]		5.422	9,760	
22	"	Proprietary composition		MLO 76-108	8.439	15,190	
23	"	"		MLO 77-114A	10.689	19,240	
24	"	"		MLO 77-114B	10.706	19,270	
25	"	"		MLO 77-114C	10.683	19,230	
26	"	"		MLO 77-123	10.483	18,870	
27	"	"		MLO 77-134	7.089	12,760	
28	"	"		MLO 77-135	7.117	12,810	
29	Lubricating oil			MIL-L-7808/ATL-7023	8.344	15,020	
30	"			MIL-L-7808/ATL-7025	8.728	15,710	
31	"			MIL-L-7808/ATL-7026	8.567	15,420	
32	"			MIL-L-23699/ATL-7022	8.139	14,650	
33	"			MIL-L-23699/ATL-7024	7.656	13,780	

[a] To enhance ignitability and completeness of combustion, benzoic acid was incorporated into the fluid samples. The heat of combustion data were corrected for the quantities of incorporated benzoic acid, presuming that it burned completely.

[b] The combustion was very incomplete, even in the presence of benzoic acid. The measured heat of combustion value is not considered reliable.

[c] Benzoic acid was incorporated into one of the two samples used for heat of combustion determination. The heat of combustion value was not affected significantly.

TABLE A-3. HOT MANIFOLD TEST RESULTS FOR MIL-H-5606C; BURETTE DELIVERY

Test sequence	Month-year	Manifold temperature °C	Manifold temperature °F	Volume[a] (ml)	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
1	6-76	654	1210	25	1		NI		Fluid stream ran off the manifold. Some droplets were temporarily retained by the rod.
		721	1330	25	1		I	1	Flames propagated to the tray by burning droplets.
		838	1540	25	1		I	<1	Flames propagated to the tray by burning droplets.
		899	1650	25	1		I	<1	Flames propagated to the tray by burning droplets.
		938	1720	25	1		I	<1	Extensive burning on the tray.
2	7-76	260	500	25	3		NI, NI, NI		Manifold surface extensively wetted. Most of the fluid flowed into the tray.
		316	600	25	[illegible]		NI, NI, NI		Manifold surface wetted. Extensive aerosol formation.
		371	700	25	3		NI, NI, NI		Manifold surface wetted. Very extensive aerosol formation.
		427	800	25	3		I, I, I	5, 4, 7	Ignition was preceded by extensive aerosol formation.
		427	800	25[b]	3		NI, NI, I	5	Extensive aerosol formation.
		482	900	25	3		NI, NI, I	6	Manifold wetted less extensively than at lower temperatures.
		538	1000	25	3		NI, NI, NI		Very limited wetting of the manifold surface by the fluid.
		593	1100	25	3		NI, NI, NI		Very limited wetting of the manifold surface by the fluid.
		649	1200	25	3		NI, NI, NI		Very limited wetting of the manifold surface by the fluid.
		704	1300	25	3		NI, NI, I	[illegible]	
		760	1400	25	3		I, I, I	2, 2, 4	Very limited wetting of the manifold surface. After ignition, intermittent burning of fluid on the manifold surface. Vigorous burning on the tray.
		927	1700	25	3		I, I, I		
3	11-76	171	340[c]	10	1		NI		Very extensive wetting of the manifold surface.
		232	450[c]	10	1		NI		Extensive wetting of the manifold surface.
		288	550[c]	10	1		NI		
		332	630[c]	10	3		NI, NI, NI		
		388	730[c]	10	3		NI, NI, NI		
		449	840	10	3		NI, NI, NI		
		510	950	10	3		NI, NI, NI		Extensive beading of the fluid on manifold surface, much less wetting.
		566	1050	10	3	35–53[d]	NI, NI, NI		Very little wetting of manifold surface by the fluid.
		610	1130	10	3		NI, NI, NI		Very little wetting; more extensive vaporization of fluid from end-segments of manifold than from the center.
		677	1250	10	3		NI, NI, NI		Fluid stream began to splatter upon impinging onto the manifold surface.
		732	1350	10	3		NI, NI, NI		Fluid stream made very little contact with the manifold surface.
		804	1480	10	3		I, I, NI		Flickering burning. During one test the fluid ignited on the cool, low end of the manifold. During another test, flickering ignition occurred twice on the hot, center section of the manifold. The flames were not propagated into the tray.

TABLE A-3 (continued)

Test sequence	Month-year	Manifold temperature °C	Manifold temperature °F	Volume[a] (ml)	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		Very extensive wetting of the manifold surface.
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	7	
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible][f]	[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	21	Intense flaming combustion of the fluid on the manifold during one experiment.
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	1.7, 7	Ignition occurred in the thermocouple area. When the fluid was allowed to flow onto the front side of the manifold, no ignition took place.
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	10, 7	Ignition occurred on the top surface of the manifold and also in the thermocouple area.
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		Wetting of the manifold occurred more rapidly than at the lower delivery rates. Liquid wavefront moved across the manifold as the burette was moved.
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	8	
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible][g]	[illegible]	11	
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]		
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	7, 8	
		[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	12, 12	Ignition occurred once in the central hot zone and once in the relatively cooler low end of the manifold.

[a]The volume of fluid consumed in experiments during which no ignition occurred. When ignition occurred, fluid deliver was discontinued, unless it was of interest to observe the burning characteristics of the fluid under the specific test conditions.

[b]The fluid being tested was heated to [illegible].

[c]Experiments conducted on [illegible] November [illegible].

[d]Experiments conducted on [illegible] November [illegible].

[e]Average fluid flow rate [illegible] ml/sec.

[f]A [illegible]-ml burette was used for fluid delivery. Average fluid flow rate [illegible] ml/sec.

[g]A [illegible]-ml burette was used for fluid delivery. Average fluid flow rate [illegible] ml/sec.

TABLE A-4. HOT MANIFOLD IGNITION TESTS RESULTS FOR MIL-H-83282; BURETTE DELIVERY

Test sequence	Month-year	Manifold temperature °C	Manifold temperature °F	Volume[a] (ml)	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
1	6-76	360	680	25	1		I	7	
		430	800	25	1		I	3	
		510	950	25	1		I	2	
		582	1080	25	1		I	2	Fluid on the tray burned for a short time.
		721	1330	25	1		I	2	Droplets extinguished in air; flames were not propagated to the tray.
		938	1720	25	1		I	<1	
2	7-76	260	500	25	3		NI, NI, NI		Less aerosol formed and more fluid flowed into the tray than with MIL-H-5606.
		316	600	25	3		I, I, I	6, 4, 4	Droplets did not propagate flames onto the tray.
		316	600	25[b]	3		NI, NI, I	3	The fluid heated to 275°F vaporized more extensively than the fluid delivered at 75°F.
		371	700	25	1		I	3	Continuous burning on the manifold.
		427	800	25	1		I	1	Continuous burning on the manifold.
		482	900	25	1		I	2	Flaming droplets extinguished upon impingement onto the tray.
		538	1000	25	1		I	2	Flaming droplets extinguished upon impingement onto the tray.
		593	1100	25	1		I	3	Intermittent flashing of the fluid on the tray.
		649	1200	25	1		I	7	Discontinuous burning of fluid on the tray.
		704	1300	25	3		I, I, I	2, 2, 5	Intermittent burning on the front rod. Rapid flowing of fluid from the manifold surface.
		760	1400	25	1		I	6	Very limited wetting of the manifold. Intermittent burning of very short durations on the manifold.
		816	1500	25	1		I	3	Intermittent burning of very short durations on the manifold.
		871	1600	25	1		I	<1	Intermittent burning of very short durations on the manifold.
		927	1700	25	3		I, I, I	<1, <1, <1	Small flamelets continuously formed on the manifold. Burning droplets extinguished before reaching the tray.

(continued)

TABLE A-4 (continued)

Test sequence	Month-year	Manifold temperature °C	Manifold temperature °F	Volume[a] (ml)	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
3	11-78	271	520[b]	10	1		NI		Manifold surface wetted by MIL-H-83282 more rapidly than by MIL-H-5606.
		332	630[c]	1010	1		NI		
		388	730[c]	10	1		I	4	
		332	630[d]	10	3	23-27[e]	NI, NI, NI		
		388	730[d]	10	2		I, I	5, 6	
		449	840	10	1		I	2	
		510	950	10	1		I	1	
		271	520[d]	25	3		NI, NI, NI		
		332	630[c]	25	3		I, I, I	13, 4.4, 4.2	Burning occurred on the manifold. The flames were propagated onto the tray.
		388	730[d]	25	3[f]		I, I, I	2.5, 4, 2	
		388	730[d]	25	2		I	1.5	
		449	840	25	1		I	1.5	Burning of fluid more intense than at 700°F manifold surface temperature.
		510	950	25	1	27-33[g]	I	1.3	
		566	1050	25	1		I	2	
		610	1130	25	1		I	3.5	
		677	1250	25	1		I	3.7	Ignition occurred in two places on the manifold - on the relatively cooler low end and on the rod in front.
		738	1360	25	1		I	<2	Ignition occurred on the rod in front.
		388	730	25[h]	1		I	2.9	
		449	840	25[h]	1		I	<1	

[a]The volume of fluid pertains to experiments during which no ignition occurred. When ignition occurred, fluid delivery was discontinued, unless it was of interest to observe the burning characteristics of the fluid under the specific test conditions.

[b]The fluid being tested was heated to 135°C/275°F.

[c]Experiments conducted on 15 November 1978.

[d]Experiments conducted on 16 November 1978.

[e]Average fluid flow rate 0.33 ml/sec.

[f]The first and third sample were from hydraulic fluid produced by the Mobil Chemical Company. The second sample was from fluid produced by the Bray Oil Company.

[g]A 25 ml burette was used for fluid delivery. Average fluid flow rate 0.85 ml/sec.

[h]100-ml burette was used for fluid delay. Average fluid flow rate ~1.5 ml/sec.

TABLE A-5. HOT MANIFOLD IGNITION TEST RESULTS FOR MIXTURES OF MIL-H-5606C AND MIL-H-83282; BURETTE DELIVERY[a]

Test sequence	Month-year	Fluid composition	Volume ratio of fluids	Manifold temperature °C	Manifold temperature °F	Number of tests	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
1	7-78	MIL-H-5606C/ MIL-H-83282	97.5/2.5	316	600	3	NI, NI, NI		Manifold surface extensively wetted. Vaporization and aerosol formation.
		"		371	700	3	NI, I, NI	5	
		"		427	800	3	I, I, NI	7, 7	Ignition was observed in vapor phase during the third experiment approximately 15 in. above the manifold.
		"		482	900	3	I, NI, I	6, 13	Ignition was observed close to or at the manifold surface during the first experiment.
2	7-78	MIL-H-5606C/ MIL-H-83282	95/5	260	500	3	NI, NI, NI		
		"		316	600	3	I, NI, I	8, 6	Extensive aerosol formation. Manifold wetted extensively.
		"		371	700	3	NI, NI, I	6	Very extensive aerosol formation.
		"		427	800	3	I, I, I	12, 3, 2	Flames propagated to the tray.
3	7-78	MIL-H-5606C/ MIL-H-83282	90/10	260	500	3	NI, NI, NI		Manifold surface wetted extensively. Most of the fluid flowed onto the tray.
		"		316	600	3	I, NI, I	8	Aerosol formation. Flames propagated to the tray during the first experiment. Fluid continued to burn in tray.
		"		371	700	3	I, I, NI	5, 3	Very extensive aerosol formation prior to ignition. Manifold surface extensively wetted.
		"		427	800	3	I, I, I	5, 5, 4	Ignition was observed in vapor phase, in the upper left, rear section of the enclosure, approximately 15 in. from manifold surface. Very vigorous fire in the tray.

TABLE A-5 (continued)

Test sequence	Month-year	Fluid composition	Volume ratio of fluids	Manifold temperature °C	Manifold temperature °F	Number of tests	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
4	7-78	MIL-H-5606C/ MIL-H-83282	75/25	316	600	3	I, I, I	3, 15, 3	Extensive aerosol formation before ignition during the second experiment. Flames propagated to the tray. Fluid continued to burn vigorously in the tray.
		"		371	700	3	I, I, I	2, 2, 15	Fluid burned in the tray.
		"		427	800	1	I	3	
5	7-78	MIL-H-5606C/ MIL-H-83282	50/50	260	500	3	NI, NI, NI		Manifold surface wetted extensively.
		"		316	600	3	I, I, I	3, 3, 2	Fluid burned in the tray.
				427	800	1	I	2	
6	7-78	MIL-H-5606C/ MIL-H-83282	25/75	316	600	3	I, I, I	2, 3, 3	Manifold surface wetted extensively prior to ignition. After ignition, fluid burned in the tray.
				427	800	1	I	1.5	Fluid burned in the tray.
7	7-78	MIL-H-5606C/ MIL-H-83282	10/90	260	500	3	NI, NI, NI		Manifold surface wetted extensively. most of the fluid flowed onto the tray.
		"		316	600	3	I, I, I	3, 2, 2	Droplets did not propagate flames onto the tray.
		"		427	800	1	I	2	Ignition was observed approximately 12 in. above the manifold, close to the back wall.

[a]Twenty-five milliliters of fluid was used for each test with mixtures of the hydraulic fluids.

TABLE A-6. HOT MANIFOLD IGNITION TEST RESULTS FOR SKYDROL® 500B; BURETTE DELIVERY[a]

Test sequence	Month-year	Manifold temperature °C	Manifold temperature °F	Volume (ml)	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
1	6-76	654	1210	25	1	∿25	NI		
		721	1330	25	1	∿25	NI		
		782	1440	25	1	∿25	I	1	Flames did not propagate to the tray.
		843	1550	25	1	∿25	I	1	Flames did not propagate to the tray.
		938	1720	25	1	∿25	I	<1	Droplets extinguished in air more rapidly than those of MIL-H-83282. Flames did not propagate to the tray.
2	7-78	927	1700	25	3		I, I, I	<1, <1, <1	Small flamelets formed intermittently on the manifold. Flames did not propagate to the tray.

[a]Twenty-five milliliters of Skydrol® 500B was used for each test.

TABLE A-7. HOT MANIFOLD SPRAY IGNITION TEST RESULTS FOR HYDRAULIC FLUIDS

Test sequence	Month-year	Fluid: Name	Fluid: Air Force designation	Fluid: Chemical class	Manifold temperature °C	Manifold temperature °F	Number of tests	Ignitability characteristics	Observations
1	6-76		MIL-H-5606C	Mineral oil-based hydrocarbon	654	1210	3	NI, NI, NI	
			"	"	721	1330	3	TI, NI, NI	Flickering flame on the back side of the manifold during the test.
			"	"	782	1440	3	IAS, IAS, IAS	
			"	"	843	1550	8	IAS, DI(1), DI, IAS, II, DI(1), DI(1), DI(1)	
			"	"	927	1700	5	II, II, II, II, NI	
2	8-76		"	"	704	1300	5	NI, NI, NI, NI, NI	
3	8-76		"	"	760	1400	4	NI, NI, IAS, NI	Ignition on the back side of the manifold during the third test.
			"	"	816	1500	6	BDI, IAS, NI	
			"	"	827	1520	3	IAS, BDI, NI	
			"	"	877	1610	5	II, II, II, II, II	
			"	"	927	1700	5	II, II, II, II, II	
4	7-78		"	"	918	1685	3	II, II, II	Very intense flames.
5	11-78		"	"	271	520	1	NI	
			"		327	620	4	NI, NI, NI, NI	Manifold was readily wetted by the fluid. Extensive vaporization.
			"	"	388	730	3	NI, NI, NI	Manifold was readily wetted. Extensive vaporization.
			"	"	449	840	3	NI, NI, NI	Manifold was still readily wetted. Very extensive vaporization.
			"	"	510	950	3	NI, NI, NI	Manifold was still extensively wetted. Most of the fluid vaporized.
			"	"	566	1050	3	NI, NI, NI	
			"	"	610	1130	3	NI, NI, NI	The fluid evaporated very rapidly from the manifold surface.
			"	"	677	1250	3	NI, NI, NI	
			"	"	738	1360	3	NI. NI, NI	
			"	"	804	1480	3	II, II, II	Ignition and vigorous combustion during spraying.
6	6-76		MIL-H-83282	Synthetic hydrocarbon	654	1210	3	NI, NI, NI	
			"	"	721	1330	3	NI, NI, NI	
			"	"	793	1460	5	DI(1), DI(1), DI(1) DI(2), BDI	

(continued)

TABLE A-7 (continued)

Test sequence	Month-year	Fluid: Name	Fluid: Air Force designation	Fluid: Chemical class	Manifold temperature °C	Manifold temperature °F	Number of tests	Ignitability characteristics	Observations
6	6-76		MIL-H-83282	Synthetic hydro-carbon	838	1540	3	DI(1), DI(1), DI(1)	
			"	"	927	1700	3	II, II, II	
7	8-76		"	"	704	1300	5	NI, NI, IAS, NI, NI	Deflector introduced into the fluid spray immediately after the solenoid valve closed.
			"	"	782	1440	5	II, IAS, IAS, IAS, IAS	
			"	"	782	1440	5[a]	BDI, BDI, BDI, BDI, BDI	Deflector introduced into the fluid spray immediately after the solenoid valve closed.
			"	"	816	1500	5	BDI, BDI, BDI, BDI, BDI	
			"	"	877	1610	5	BDI, BDI, BDI, BDI BDI	
			"	"	932	1710	6	II, II, II, II, II, II	
8	7-78		"	"	918	1685	3	II, II, II	Very intense flames.
9	11-78		"	"	332	630	2	IAS, IAS	
			"	"	388	730	3	IAS, IAS, IAS	
			"	"	449	840	3	NI, IAS, IAS	Fluid evaporated rapidly from the manifold surface.
			"	"	510	950	3	NI, NI, NI	
			"	"	566	1050	3	NI, NI, NI	
			"	"	610	1130	3	NI, NI, NI	
			"	"	677	1250	3	I, NI, NI	
			"	"	738	1360	3	II, II, II	
10	6-76	Skydrol® 500B		Phosphate ester	654	1210	3	NI, NI, NI	
		"		"	721	1330	3	NI, NI, NI	
		"		"	788	1450	4	NI, NI, NI, NI	
		"		"	827	1520	4	IAS, DI, NI, NI	
		"		"	888	1630	3	BDI, BDI, BDI	Droplets did not propogate flames to the tray.
		"		"	927	1700	3	II, II, II	
11	8-76	"		"	760	1400	5	NI, NI, NI, NI, NI	
		"		"	816	1500	5	TI, NI, NI, NI, NI, NI	Few small flashes observed during the first test.
		"		"	866	1590	5	BDI, BDI, BDI, BDI, BDI	
		"		"	935	1715	6	II, II, II, II, II II	
12	7-78	"		"	918	1685	3	II, II, II	

[a] 1.3-sec burst of fluid spray used during these experiments, instead of the usual 1.0-sec bursts.

TABLE A-8. HOT MANIFOLD IGNITION TEST RESULTS FOR CANDIDATE NONFLAMMABLE AND EXPERIMENTAL HYDRAULIC FLUIDS; BURETTE DELIVERY

Month-year	Fluid: Name	Fluid: Air Force designation	Manifold temperature °C	Manifold temperature °F	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
1-77	Brayco® 814Z	MLO 76-107	930	1700	1	29	NI		
7-78	"		930	1700	3		NI, NI, NI		
1-77	Freon® E6.5	MLO 76-119	930	1700	1	17	NI		
7-78	"		930	1700	3		NI, NI, NI		
6-76	Halocarbon® AO-8	MLO 76-29	760	1400	1		NI		
	"	"	816	1500	1		TI	10	One flamelet observed.
	"	"	871	1600	1		TI		Some flickering flames; primarily on the back side of the manifold.
	"	"	938	1720	3		TI		Flickering flames observed above the rod and on the back side of the manifold.
8-76	"	MLO 76-74	854	1570	1		NI		Burette moved.
	"	"	916	1680	1		TI		Burette held stationary.
	"	"	916	1680	1		TI		Burette moved.
1-77	"	"	871	1600	1	15	NI		
	"	"	927	1700	2	18	TI		Small flames on the back surface of the manifold. Small flames in the beginning of the second test.
	"	"	960	1760	1	25	TI		Small flames.
1-77	"	MLO 76-122	871	1600	1	15	NI		
	"	"	927	1700	1	21	TI		Small flames on the back surface of the manifold.
7-78	"		927	1700	3		I, NI, NI		Flickering flame observed once on back side of manifold.
11-78	"		388	730	1		NI		
	"		449	840	1		NI		
	"		510	950	1		NI		
	"		566	1050	1		NI		
	"		610	1130	1	16-21	NI		
	"		677	1250	1		NI		
	"		738	1360	1		NI		
	"		804	1480	1		NI		
	"		871	1600	1		NI		
1-77	Halocarbon® AO-8 formulation	MLO 76-135	871	1600	1	18	NI		
		"	927	1700	2	24	NI, TI		Flickering flame observed once. Resinous solid formed in the tray.
	"	"	960	1760	1	19	TI		More frequent ignition than at 1700°F. Burning not continuous. Flames not propagated to tray.

(continued)

TABLE A-8 (continued)

Month-year	Fluid: Name	Fluid: Air Force designation	Manifold temperature °C	Manifold temperature °F	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
3-77	Halocarbon® AO-8 formulation	MLO 77-47	921	1690	1		TI		Transitory ignition.
1-77		MLO 72-109[a]	927	1700	2	39, 52	NI, NI		
3-77	Nadraul MS-6	MLO 77-41	438	820	2		NI, NI		
	"	"	477	890	2		BDI		Residue remained on manifold surface.
	"	"	504	940	2		BDI		
	"	"	571	1060	2		I, I		Silica residue remained on manifold surface after organic matter burned completely.
5-77	Nadraul MS-6		427	800	1	50	NI		
	"		482	900	1		BDI		Continuous burning on the manifold and tray. Porous oxide coating formed on manifold absorbed fluid and prolonged burning.
	"		538	1000	1		BDI		
7-78	Nadraul MS-6		927	1700	3		I, I, I	2, <1, <1	Continous burning of progressively increasing intensity on manifold. Flaming droplets extinguished before impinging onto tray.
5-77		MLO 73-51[b]	316	600		13	NI		
			371	700		12	I	6	Flames propagated to tray.
			427	800	1	15	I	8	Flames propagated to tray.
			482	900	1		I	1	Vigorous burning on manifold and in tray.
5-77		MLO 73-62[b]	316	600	1	15	NI		
			371	700	1	14	I	1	Continuous burning on the manifold. Intermittent burning on tray.
			427	800	1	14	I	2	Continuous burning on the manifold and tray.
			482	900	1		I	3	Continuous burning on the manifold and tray.
7-78		MLO 73-34[b]	260	500	3		NI, NI, I	4	Fluid wetted the surface extensively. More fluid flowed into the tray than vaporized.

(continued)

TABLE A-8 (continued)

Month-year	Fluid: Name	Fluid: Air Force designation	Manifold temperature °C	Manifold temperature °F	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
7-78		MLO 73-94[b]	316	600	3		I, I, I	3, 3, 3	Falling droplets carried flames further than those of MIL-H-83282.
		"	371	700	1		I	1.5	After impingement, the droplets burned for a short duration on tray.
		"	427	800	1		I	1	Ignition was observed to occur in vapor phase.
		"	482	900	1		I	1	
		"	538	1000	1		I	4	Continuous flaming on manifold. Flames propagated to tray. Fluid continued to burn in the tray.
		"	593	1100	1		I	2	Less intense burning on manifold than at 1000°F.
		"	649	1200	1		I	3	Flaming on manifold became intermittent.
		"	704	1300	1		I	3	Fluid ignited intermittently on colder parts (ends) of manifold.
		"	760	1400	1		I	2	Flickering flamelets were observed twice.
		"	816	1500	1		I	2	Intermittent, small flashes observed on the manifold.
		"	871	1600	1		I	1	Intermittent burning on manifold, continuous burning on tray.
5-77		MLO 74-53[b]	316	600	1	15	NI		
			371	700	1	15	I	2	Continuous burning on the manifold. Intermittent burning on the tray.
			427	800	1	13	BDI	<1	Continuous burning on the manifold. Intermittent burning on the tray.
			482	900	1		I	3	Continuous vigorous burning on the manifold and the tray.

[a]Fluoroalkyl ether-substituted triazine.

[b]Synthetic hydrocarbon.

TABLE A-9. HOT MANIFOLD SPRAY IGNITION TEST RESULTS FOR CANDIDATE NONFLAMMABLE AND EXPERIMENTAL HYDRAULIC FLUIDS

Test sequence	Month-year	Fluid: Name	Fluid: Air Force designation	Fluid: Chemical class	Manifold temperature °C	Manifold temperature °F	Number of tests	Ignitability characteristics	Observations
1	7-78	Brayco® 814Z		Fluoroalkyl ether	893	1640	3	NI, NI, NI	Manifold cooled by the spray.
2	6-76	Halocarbon® AO-8	MLO 76-29	Chlorofluorocarbon	927	1700	6	NI, NI, NI, NI, NI, NI	
3	8-76	"	MLO 76-74	"	866 929	1590 1705	5 5	NI, NI, NI, NI, NI NI, NI, NI, NI, NI	
4	7-78	"		"	888	1630	3	NI, NI, NI	Manifold cooled by the spray.
5	7-78	Freon® E6.5		Fluoroalkyl ether	888	1630	3	NI, NI, NI	Manifold cooled by the spray
6	5-77	Nadraul MS-6		Silicone	482 538	900 1000	1 1	NI II	
7	7-78	"		"	886	1630	3	II, II, II	Very bright flame. Silica deposit formed on the manifold.

TABLE A-10. HOT MANIFOLD IGNITION TEST RESULTS FOR FUELS AND SILICATE ESTER FLUIDS; BURETTE DELIVERY[a]

Test sequence	Month-year	Fluid	Manifold temperature °C	Manifold temperature °F	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
1	5-77	JP-4	482	900	1	19	NI		
		"	538	1000	1	17	NI		
		"	593	1100	1	15	NI		
		"	649	1200	1	13	NI		
		"	704	1300	2		I, I	4, 7	Intense flames propagated to the tray.
2	5-77	JP-5	482	900	1	22	NI		
		"	538	1000	1	16	NI		
		"	593	1100	1	13	NI		
		"	649	1200	1	15	NI		
		"	704	1300	1		I	6	Intense flames propagated to the tray.
3	5-77	JP-7	482	900	1	18	NI		
		"	538	1000	1	16	NI		
		"	593	1100	1	13	NI		
		"	649	1200	1	13	NI		
		"	704	1300	2		I, I	2	Intense flames propagated to the tray.
4	5-77	JP-8	482	900	2	16	NI, NI		
		"	538	1000	1	15	NI		
		"	593	1100	1	11	NI		
		"	649	1200	1		I	7	Intense flames propagated to the tray.
5	5-77	JP-9	482	900	1	18	NI		
		"	538	1000	1	16	NI		
		"	593	1100	1	12	NI		
		"	649	1200	1	9	NI		
		"	704	1300	1		I	1	Intense flames propagated to the tray.

(continued)

TABLE A-10 (continued)

Test sequence	Month-year	Fluid	Manifold temperature °C	Manifold temperature °F	Number of tests	Fluid delivery time(s) (sec)	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
6	5-77	RJ-5	482	900	1	22	NI		
		"	538	1000	1	23	NI		
		"	593	1100	2		I, I	2, 5	Intense flames propagated to the tray.
		"	704	1300	1		I	3	Intense flames propagated to the tray.
7	7-78	Chevron M2V[b]	316	600	3		NI, NI, NI		Manifold surface extensively wetted by the fluid.
		"	371	700	3		I, I, I	3, 3, 5	Continuous burning on the manifold after ignition. Intermittent localized burning on the tray at location where droplets impinged. Thin silica deposit formed a manifold.
		"	927	1700	3		I, I, I	<1, <1, <1	Continuous burning on the manifold, intermittent burning on the tray. Thin silica deposit formed on the manifold.
8	7-78	Coolanol® 25R[c]	316	600	3		NI, NI, NI		Manifold surface extensively wetted by the fluid.
		"	371	700	3		I, I, I	3, 2, 2	Continuous burning on the manifold after ignition. Continuous burning also on the tray, in areas where the fluid stream impinged.
		"	927	1700	3		I, I, I	<1, <1, <1	

[a]Twenty-five milliliters of fluid was used for each test.

[b]Silicate ester type hydraulic fluid.

[c]Silicate ester type heat transfer fluid.

TABLE A-11. HOT MANIFOLD IGNITION TEST RESULTS FOR HYDRAULIC FLUIDS, LUBRICATING OILS AND HALON 1211; BEAKER DELIVERY

Test sequence	Month-year	Fluid	Manifold temperature °C	Manifold temperature °F	Number of tests	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
1	10-76	Krytox® (MLO 76-72)	927	1700	1[a]	NI		
		"	966	1770	1[a]	NI		
2	11-78	MIL-H-5606C	316	600	1[a]	NI		
		"	371	700	1[b]	NI		
		"	427	800	1[b]	NI		
		"	482	900	1[b]	I		
		"	538	1000	1[b]	I		
		"	593	1100	1[b]	I	?	Flames did not propagate to the tray.
		"	649	1200	2[b]	I, I		
		"	704	1300	1[b]	I		Ignition occurred in the relatively cooler, low section of the manifold.
		"	760	1400	1[b]	I		Flames propagated to the tray.
3	5-77	MIL-L-7808/ATL-7023	482	900	1[c]	NI		Very extensive vaporization and aerosol formation.
		"	538	1000	1[c]	NI		Very extensive vaporization and aerosol formation.
		"	593	1100	1[c]	NI		Very extensive vaporization and aerosol formation.
		"	649	1200	1[c]	NI		Very extensive vaporization and aerosol formation.
		"	704	1300	3[c]	I, NI, NI	<1	Ignition occurred on the rod, on the front side of the manifold.
4	5-77	MIL-L-7808/ATL-7025	482	900	1[c]	NI		Very extensive vaporization and aerosol formation.
		"	538	1000	1[c]	NI		Very extensive vaporization and aerosol formation.
		"	593	1100	1[c]	NI		Very extensive vaporization and aerosol formation.
		"	649	1200	1[c]	NI		Very extensive vaporization and aerosol formation.
		"	704	1300	3[c]	I, I, I	<1, <1, <1	Flames not very intense.

TABLE A-11 (continued)

Test sequence	Month-year	Fluid	Manifold temperature °C	Manifold temperature °F	Number of tests	Ignitability characteristics	Approximate ignition delay time(s) (sec)	Observations
5	5-77	MIL-L-7808/AFL-7026	482	900	3[c]	NI		Very extensive vaporization and aerosol formation.
		"	538	1000	3[c]	NI		Very extensive vaporization and aerosol formation.
		"	593	1100	3[c]	NI		Very extensive vaporization and aerosol formation.
		"	649	1200	3[c]	NI		Very extensive vaporization and aerosol formation.
		"	704	1300	3[c]	I, I, I	<1, <1, <1	Flames carried by falling droplets, extinguished upon impingement onto the tray.
6	5-77	MIL-L-23699/AFL-7023	482	900	3[c]	NI		Very extensive vaporization and aerosol formation.
		"	538	1000	3[c]	NI		Very extensive vaporization and aerosol
		"	593	1100	3[c]	I, I, NI	<1, <1	Burning did not continue on the tray.
		"	649	1200	3[c]	I	<1, <1, <1	Flames propagated to the tray; burning continued on the tray.
7	5-77	MIL-L-23699/AFL-7024	482	900	3[c]	NI		Very extensive vaporization and aerosol formation.
		"	538	1000	3[c]	NI		Very extensive vaporization and aerosol formation.
		"	593	1100	3[d]	NI		Very extensive vaporization and aerosol formation.
		"	649	1200	3[c]	I, I, NI	<1, <1	Burning did not continue on the tray.
		"	704	1300	3[c]	I, I, NI	<1, <1	Burning did not continue on the tray.
8	11-78	Halon 1211	916	1680	3[a]	NI, NI, NI		

[a]Twenty-five milliliters of fluid used. Delivery times were ~10 sec.

[b]Up to 50 ml of fluid used.

[c]Approximately 10 ml of fluid used.

TABLE A-12. HOT MANIFOLD SPRAY IGNITION TEST RESULTS FOR LUBRICATING OILS AND SILICATE ESTER FLUIDS[a]

Test sequence	Month-year	Fluid: Name	Fluid: Air Force designation	Fluid: Chemical class	Manifold temperature °C	Manifold temperature °F	Number of tests	Ignitability characteristics	Observations
1	5-77		MIL-L-7808/ATL-7033	Aliphatic ester	704	1300	3	NI, NI, NI	
			"	"	760	1400	3	NI, NI, NI	
			"	"	816	1500	3	IAS, IAS, IAS	Not very intense flames.
			"	"	871	1600	3	BDI, BDI, BDI	Intense flames.
2	4-77		MIL-L-7808/ATL-7025	"	760	1400	3	NI, NI, NI	
			"	"	816	1500	3	BDI, BDI, BDI	
3	-77		MIL-L-7808/ATL-7026	"	760	1400	3	NI, NI, NI	
			"	"	816	1500	3	BDI, BDI, BDI	
4	5-77		MIL-L-23699/ATL-7027	"	760	1400	3	NI, NI, NI	
			"	"	816	1500	3	IAS, BDI, BDI	
5	5-77		MIL-L-23699/ATL-7024	"	760	1400	3	NI, NI, NI	
			"	"	816	1500	3	IAS, IAS, IAS	
6	7-78	Chevron M2V[b]		Silicate ester	893	1640	3	II, II, II	Very bright flames.
7	7-78	Coolanol® 25R[c]		"	888	1630	3	II, II, II	Intense flames. Thin silica deposit formed on the manifold.

[a]One-second bursts of fluid spray used.

[b]Hydraulic fluid.

[c]Heat transfer fluid.

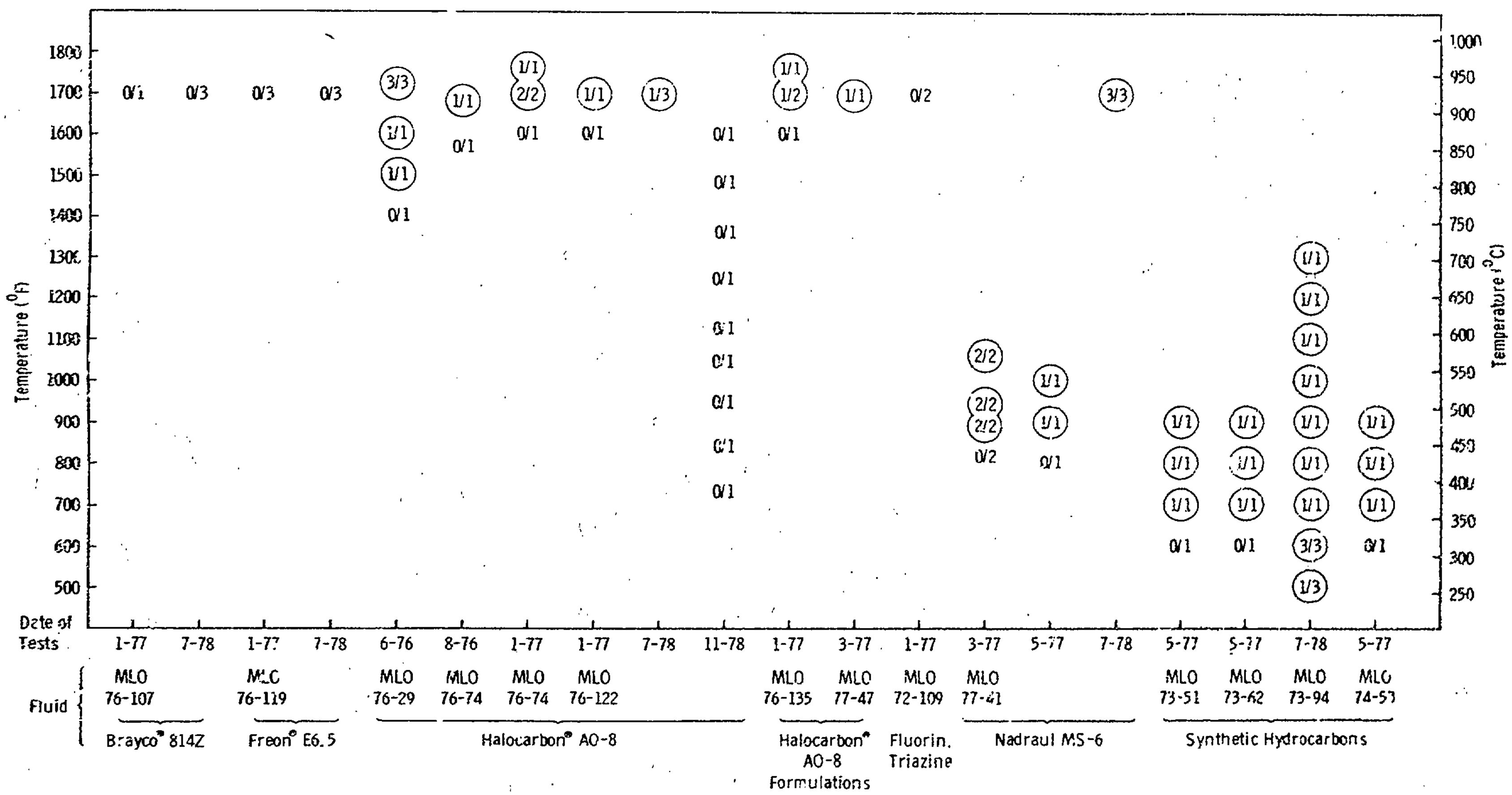

Figure 32. Hot manifold ignition test results for candidate nonflammable and experimental hydraulic fluids with liquid stream impingement.

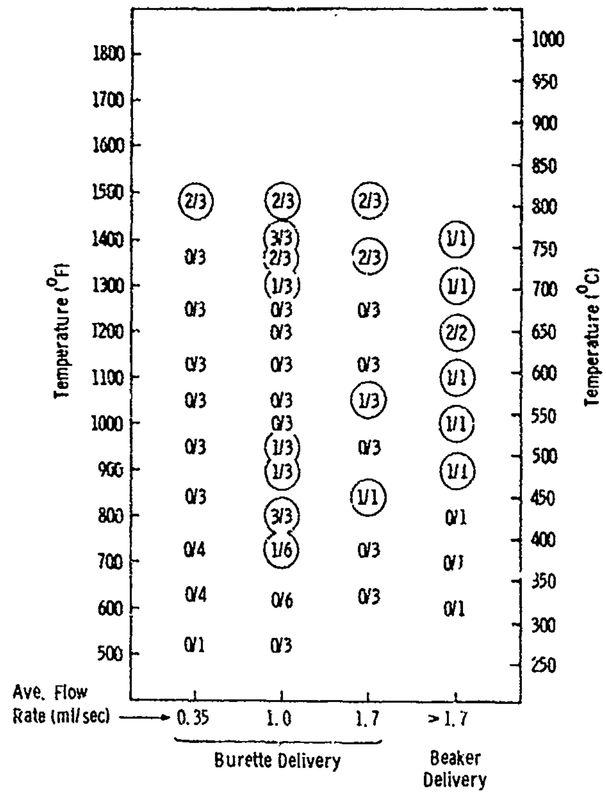

Figure 33. Hot manifold ignition test results for MIL-H-5606 with liquid stream impingement.

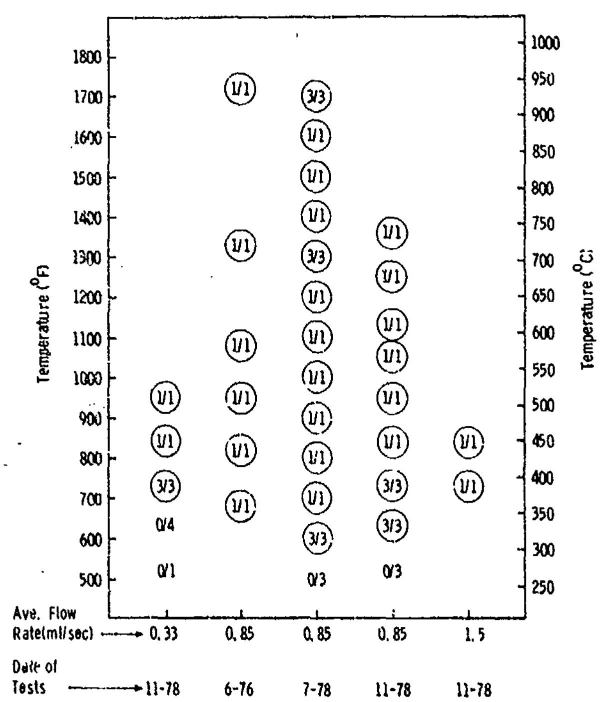

Figure 34. Hot manifold ignition test results for MIL-H-83232 with liquid stream impingement.

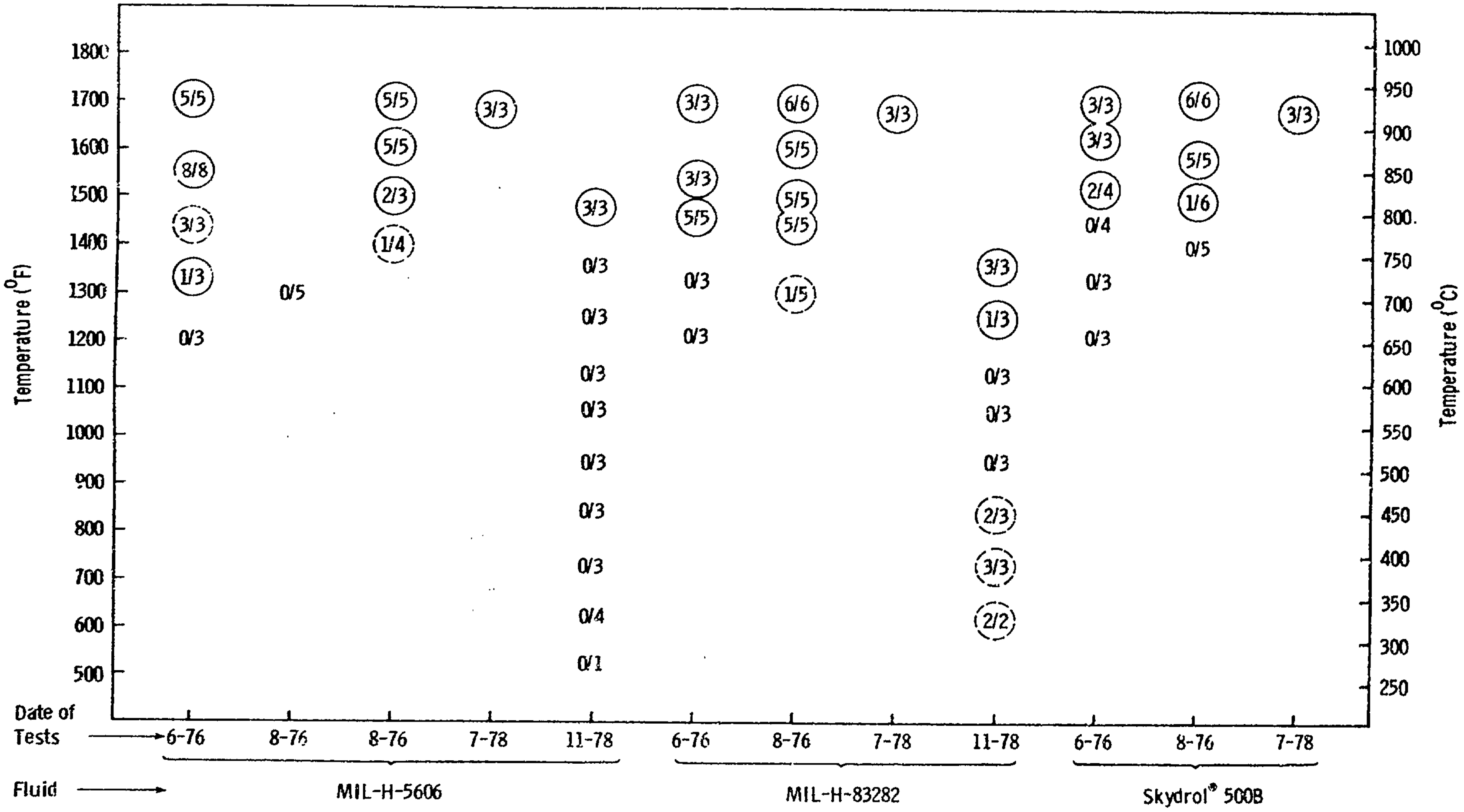

Figure 35. Hot manifold spray ignition test results for hydraulic fluids.

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